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WYNDvalley: An Air-Quality Model for Near-Stagnant Flows in Constricted Terrain

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On Air-Quality Modeling in Complex Terrain, with Emphasis on WYNDvalley, A Dispersion Model for Near-Stagnant Flows

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The mathematics of air-quality modeling is discussed with special attention to problems associated with complex terrain. Practical solutions to some of these problems are suggested and an implementation is described as WYNDvalley, a dispersion model adapted to the study of trace species concentrations in near-stagnant conditions within complex valley drainage systems. The model is illustrated by application to the Methow, Twisp, and Chewack valleys of Okanogan County, Washington.

I. Introduction

To guide wise management of the air we live in, we wish to develop models and simulations to permit accurate estimates of the concentrations of air pollutants, appropriately averaged over time and space. This is a difficult task. The motions of the air are characterized by erratic vascillations that display temporal scales between seconds and seasons, and spatial scales between millimeters and thousands of kilometers. Limitations of cost affect the density of observations that we may make to specify the initial state of the systems we wish to model, and to follow the evolution of the winds and emissions throughout the period that interests us. Perhaps surprisingly in these times of exponentially improving computer technology, we are also limited by the computer speeds and memory that would be needed for near-rigorous solutions to the equations we pose. For these reasons practical progress requires approximation.

In the following section I shall explore alternate choices for these approximations, starting from common assumptions and with moderate rigor. Here I shall emphasize practical implementation of computer models to be useful under conditions when the flows are dominated by constraints imposed by local topography. In section III I shall illustrate these choices in more detail through a specific model, *WYNDvalley,* and discuss some results from a specific simulation, the sensitivities of these results to the data and to the model's assumptions, accuracies

and limitations, ways the model might be improved, and the likely costs and benefits of effort to effect these improvements. I conclude with a summary and documentary appendices.

II. Some Mathematics of Tracer Dispersion in the Atmosphere

Readers anxious to get on with specific details of *WYNDvalley* may turn immediately to section III.

My purpose in including the present discussion is to make explicit a rather long series of approximations that must be introduced along the way towards solutions of equations over which ... as it seems to me ... unnecessary arguments sometimes erupt about the merits of alternate and disparate seeming algorithms. The point is that excessive partisanship over 'Gaussian Plume' or 'Box' models is ... or ought to be ... somewhat vitiated by an appreciation of the many severe approximations that are common to both these useful approaches.

In the sub-sections that follow I shall highlight those approximations that are common to both Gaussian and box models, and those separate to each. I shall conclude this section with a discussion of the virtues and limitations of the two approaches to air-quality modeling, with emphasis on matching models to the questions that are to be asked of them.

A. The Dispersion Equation: General Approximations

The central concept of tracer dispersion is, very simply, that mass must be conserved. The governing equation is:

$$\frac{\partial C}{\partial t} = -\nabla \cdot \left[\mathbf{u}C\right] + Q \qquad [1]$$

In [1] $C(x,y,z,t)$ is the concentration of a trace chemical species whose motions and dispersion we wish to model as functions of the spatial coordinates x,y,z, and time t; ∇ is a generalized representation of the gradient operator which, in Cartesian coordinates, becomes $\mathbf{d/dx + d/dy + d/dz}$. The wind velocity is $\mathbf{u}(x,y,z,t)$ and $Q(x,y,z,t)$ is a source or sink. The bold fonts emphasize that ∇ and $\mathbf{u}$ are vectors [while C and Q are scalars] and the central dot between the vectors denotes the scalar product.

One can imagine solving [1] directly by numerical integration: set up a three dimensional grid, specify $C(x,y,z,t_o)$, $u(x,y,z,t)$ and $Q(x,y,z,t)$, and then use Euler's rule .. or other convenient algorithm .. to solve for $C(x,y,z,t_o+dt)$.

Problems arise, however, because very small increments must be specified in each of the coordinates. We have all seen near-neighbor wind flags blowing in disparate directions, and we have all experienced wind speeds and directions that change abruptly within a few seconds. Suppose then, for illustration, that we specify a grid with 10 meter resolution over a 10 km x 10 km x 1 km box. This would require 10^8 grid elements just to specify the instantaneous concentration field. I understand that there are parallel machines that can do this, barely, but for our purposes the most apt comparison may be to the CRAY I, that in one common configuration can address 'only' 7×10^6 random-access memory locations. Ignoring this, just for the illustration, with 10 second time resolution for the simulated fields, and 10 Mhz computational clock speed with 10 cycles per 4-byte multiplication, this brute-force integration would require approximately 10 computer minutes per simulated hour. That is, the computer would be running only six times faster than the world, for a 10 km x 10 km x 1 km box that often would be too small for our interest, anyway.

This illustration is silly for a further important reason: we simply cannot afford the density of measuring instruments necessary to specify the initial concentrations and winds in those 10^8 grid elements, nor to verify the precision of our calculations, after the fact.

For these reasons, let us proceed to condition equation [1] for approximations that are forced upon us anyway by the intrinsic variability of our noisy atmosphere.

First let's try to stretch out the time unit for each integration step. Notice that in the brute-force example above, a ten second time step is limited to wind speeds of less than one meter per second, across the grid lengths of ten meters. But most measurements will report winds and tracer concentrations that have been averaged over tens of minutes, or hours, and often at speeds exceeding 1 m/s.

To spread out the time steps, let's define:

$$\bar{\xi}(x,y,z) = \frac{1}{\tau}\int_{-\tau/2}^{+\tau/2} \xi(x,y,z,t')\,dt' \qquad [2]$$

where ξ may be either the concentration, C, the source, Q, or any component of the wind velocity, u. The time, τ is a somewhat imprecisely defined subscale over which we want to smooth our equation variables to match more closely the real averaging times of our measurements.

With [2] we next define primed quantities such that:

$$C(x,y,z,t) = \bar{C}(x,y,z) + c'(x,y,z,t) \qquad [3c]$$

$$Q(x,y,z,t) = \bar{Q}(x,y,z) + q'(x,y,z,t) \qquad [3q]$$

$$u(x,y,z,t) = \bar{u}(x,y,z) + u'(x,y,z,t) \qquad [3u]$$

$$v(x,y,z,t) = \bar{v}(x,y,z) + v'(x,y,z,t) \qquad [3v]$$

$$w(x,y,z,t) = \bar{w}(x,y,z) + w'(x,y,z,t) \qquad [3w]$$

In [3] the barred quantities are time-averaged over τ and the primed quantities express the more slowly varying fluctuations at times greater than τ; u, v, and w are the three scalar components of the vectorial wind, respectively parallel to x, y, and z. Note that by definition:

$$\overline{c'} = \overline{q'} = \overline{u'} = \overline{v'} = \overline{w'} = 0 \qquad [2']$$

Substituting [3u] back into [1], while temporarily neglecting the coordinates y and z:

$$\frac{dC}{dt} = -\frac{d}{dx}\left[(\bar{C} + c')(\bar{u} + u')\right] + (Q + q') \qquad [1a]$$

Expanding and with a second overbar to denote averaging the operators of [1a] over τ,

$$\overline{\frac{dC}{dt}} = -\overline{\frac{d}{dx}\left(\bar{C}\bar{u} + \bar{C}u' + \bar{u}c' + u'c'\right)} + \bar{Q} + \overline{q'} \qquad [1b]$$

The middle two terms within the [ ] average to zero by definition [2'], as does $\overline{q'}$. Then dropping double overbars and noting that $\overline{\bar{u}\bar{C}} = \bar{u}\bar{C}$,

$$\frac{d\bar{C}}{dt} = -\frac{d}{dx}\left[\bar{u}\bar{C} + \overline{u'c'}\right] + \bar{Q} \qquad [1c]$$

The effect of this manipulation is to lump into the $\overline{u'c'}$ all the temporal fluctuations that occur in times that are short with respect to τ, the measurement time. Since by definition this term is *not* measured, it has to be modeled. What shall we do with it?

We could set it equal to zero: that after all is a model, too. But this vigorous approximation excessively degrades the accuracy of what we're trying to do. One useful approach is to write additional differential equations of the form

$$\frac{d\overline{u'c'}}{dt} = F\left[\overline{u'^2}, \overline{c'^2}, \overline{u'c'}, \cdots\right]$$

but this expansion rapidly increases the complexity of the equation set, and closure problems intrude with higher-order moments.

By far the most common approach is to model the $\overline{u'c'}$ in terms of the quantities that are measured at the time scale, τ, namely $\overline{u}$ and $\overline{C}$. This is the natural 'next higher approximation'. Drawing heavily upon analogies to the diffusion of heat in rigid bodies [an imperfect analogy that will causes trouble later, because the air is *not* rigid], Batchelor, Prandl, Reynolds, Richardson, and many others have explored the utility of postulating:

$$\overline{u'c'} = -K_z \frac{dC}{dz} \qquad [4]$$

For obscure reasons this is called the 'exchange' approximation (or the 'austasch' approximation by those who wish to make it even more obscure). The K_z defined by [4] is ultimately an empirical coefficient, called a diffusivity. It has dimensions of length^{2}time^{-1}, and it may be thought of as the product of a root-mean-square 'eddy velocity' times a scale length over which these eddies are effective in transporting momentum. The subscript z denotes that K_z is a scalar component of the vector **K**. Some authors generalize [4] still further by defining **K** as a tensor, but this is really just mathematical exhibitionism: remember that the components of **K** are ultimately empirical and can be measured in ways that force a vectorial interpretation.

Now we can proceed by substituting [4] into [1c], hereafter dropping the overbar notation as excessively busy; remember, however, that all the measurements and modeled variables remain implicitly as averaged over τ. We get:

$$\frac{\partial C}{\partial t} = \left(\frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}\right)\left[-uC + K_x\frac{\partial C}{\partial x} + K_y\frac{\partial C}{\partial y} + K_z\frac{\partial C}{\partial z}\right] + Q \qquad [1d]$$

In [1d] the y- and z- dimensions have been put back again to help make clear some approximations that follow. Specifically, let us now line up the coordinate system so that the mean wind (averaged over t) is parallel to the x-axis, and then assume:

$$\frac{\partial(vC)}{\partial x} = \frac{\partial(wC)}{\partial x} = \frac{\partial(uC)}{\partial y} = \frac{\partial(wC)}{\partial y} = \frac{\partial(uC)}{\partial z} = \partial\frac{(vC)}{\partial z} = 0 \qquad [5a]$$

and

$$\left[\frac{\partial}{\partial x}\ \frac{\partial}{\partial y}\ \frac{\partial}{\partial z}\right]\begin{Bmatrix} K_x\frac{dC}{dx} & K_x\frac{dC}{\partial y} & K_x\frac{dC}{dz} \\ K_y\frac{dC}{dx} & K_y\frac{dC}{\partial y} & K_y\frac{dC}{dz} \\ K_z\frac{dC}{dx} & K_z\frac{dC}{\partial y} & K_z\frac{dC}{dz} \end{Bmatrix} \text{ is diagonal} \qquad [5b]$$

Condition [5a] is just a statement that the $\overline{u'c'}$, $\overline{v'c'}$, and $\overline{w'c'}$ do not affect the orthogonality of the x-y-z coordinate system. [This is *not* equivalent to stating that the turbulence is isotropic.] Condition [5b] again states that the diffusivities coordinate system, and [5b] again states that the diffusivities need not be treated as tensors. In comparison to other approximations that follow, neither [5a] or [5b] are very severe.

With these approximations [1d] simplifies to:

$$\frac{\partial C}{\partial t} = -\frac{\partial(uC)}{\partial x} - \frac{\partial(vC)}{\partial y} - \frac{\partial(wC)}{\partial z} + \frac{\partial}{\partial x}\left[K_x\frac{\partial C}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_y\frac{\partial C}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_z\frac{\partial C}{\partial z}\right] + Q \qquad [1e]$$

In [1e] the K_x, K_y, and K_z have so far been left within the exterior spatial differential operators to emphasize that they are in fact functions of scale. This property of the atmosphere makes eddy diffusion fundamentally different from that of heat in rigid solids. Measurements over widely differing scales show that atmospheric diffusivities are larger for bigger puffs than smaller [See for example: Gifford, 1982]. At scales larger than about 30 km eddy-diffusivity coefficients scale roughly as λ^2, where λ is a curvature scale of a diffusing puff, that may or may not be isotropic.

At smaller scales K_x, K_y, and K_z vary with diminishing powers of λ_x, λ_y, and λ_z, but they do not approach scale independence until puff sizes of millimeters, or less.

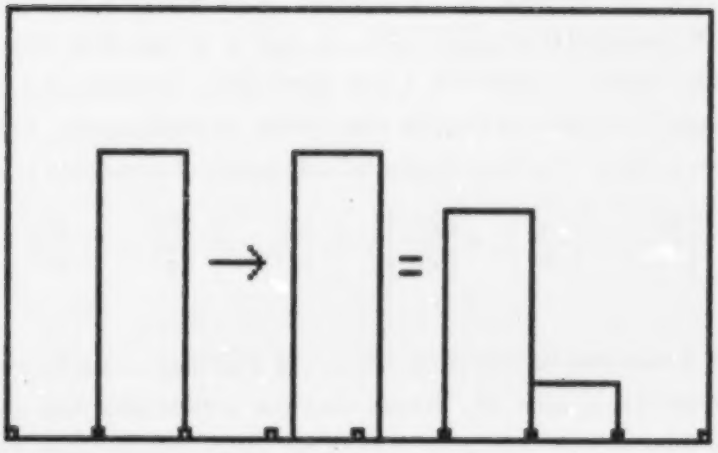
To proceed with any elegance beyond [1e] therefore requires differentiation at all scales, a need perhaps best assuaged by spectral expansions of the variables in Fourier series. Alternately, with less elegance but perhaps more common sense, one may ignore the scale dependence of the K_ℓ at this step, and proceed with the differentiations as if the they were scale independent; then at a later step empirical scale corrections can be imposed *a posteriori*. It is further a common approximation to neglect the spatial gradients of u, v, and w at this step, though in fact this is not strictly required ... nor is it a very good idea. However, for simplicity and because Gaussian models *do* require this further approximation, I shall make it here to achieve a 'final' working version of this series of equations [1]:

$$\frac{\partial C}{\partial t} = -u\left[\frac{\partial C}{\partial x}\right] - v\left[\frac{\partial C}{\partial y}\right] - w\left[\frac{\partial C}{\partial z}\right] + K_x\frac{\partial^2 C}{\partial x^2} + K_y\frac{\partial^2 C}{\partial y^2} + K_z\frac{\partial^2 C}{\partial z^2} + Q \qquad [1f]$$

Let us pause for a moment to reflect on what ... if anything ... useful that we have done by recasting [1] into [1f]. Recall that the central idea was to subsume all the temporal fluctuations that occur over time scales smaller than the measurements' averaging times, τ, into terms of the form $\overline{u'c'}$, and then through the 'exchange' approximation to parameterize these into K_ℓ. This *may* permit us both larger time steps and a wider spatial net, because at constant wind speeds each parcel travels further during the longer times. Unfortunately, however, this latter advantage is not automatic, as a new and serious difficulty intrudes when we attempt to integrate [1f] numerically with a relaxed grid.

This trouble is perhaps best illustrated with a sketch, as in figure 1. Suppose that an initial puff concentration is uniformly spread between two adjacent grid points, as with the prism at the left of the figure. With a wind blowing to the right, then after a time increment dt the puff might be translated to the position of the center prism. But with a finite grid the mass distribution of this puff would be interpreted as split between the two adjacent grid elements, as with the pair of prisms at the right. Suddenly the puff has 'diffused' to greater width, purely as an artifact of the finite grid. Unless the translation fortuitously places the puff exactly over a neighboring grid, which is hard to achieve generally when

Figure 1



Numerical Diffusion

the winds vary in direction and speed, the numerical diffusion may easily exceed the physical diffusion. One may minimize this artifact by requiring tight grids, but this is a step backwards in the whole approach from [1] towards [1f].

What is to be done about this new problem? Two approaches are common: brute force, or a clever transform. Both have virtues and defects. The *WYNDvalley* model that will be described in the next section is essentially a brute-force approach: set up a moderately fine grid (100's of meters) with moderately small integration steps (100's of seconds), accept moderate numerical diffusion, but compensate for it by diminishing the external diffusion parameters, K_ℓ. The advantages and limitations of this approach will be described in appropriate detail later. Because the transform approach is the more commonly used, however, it is proper here to continue its development for a few more paragraphs, to illuminate the comparison.

B. Gaussian Models: Special Approximations

In this sub-section I amplify briefly on an additional set of approximations inherent in Gaussian solutions to [1f].

If u, v, and w are approximately constant over short times and spaces, then [1f] is a linear second order differential equation. Several of the approximations leading to [1f] where consciously adapted to achieve linearity, so as to take advantage of a convenient property of linear equations, that two independent solutions of [1f] may be added to one another to make a a third. Thus if we can derive an analytical solution to [1f] for an infinitesimal puff, then we may superimpose puff solutions to achieve a general solution. This approach leads to the justly famous 'Gaussian' models.

While the derivation of a Gaussian solution to [1f] is straight forward, it is also rather lengthy, and it would overbalance the present text. Interested readers should therefore consult other references [see for example: Pasquill and Smith., 1983; Longhetto, 1980]. For present purposes permit me to sketch the derivation, only, for the more common 'plume' version. A more complex 'puff' version may be derived similarly, with somewhat fewer restrictions.

1. Assume a steady-state for times less than τ. Temporal changes at times greater than τ will be accounted for by specifying slower variations in the winds and diffusivities.
2. Neglect diffusion parallel to the wind: that is, set $K_x = 0$.
3. Set $\partial C/\partial t = 0$ and seek a solution for the remaining partial derivatives in x, y, z, of the form $X(x)Y(y)Z(z)$.
4. Substituting XYZ into [1f], and rearranging one may separate the partial differential equation into three total differential equations, one for x, one for y, and one for z. These have particular solutions of the form

$$X(x) = C_1 e^{-kx}$$

$$Y(y) = C_2 \sin(\Omega_y y) + C_3 \cos(\Omega_y y)$$

$$Z(z) = C_4 \sin(\Omega_z z) + C_5 \cos(\Omega_z z)$$

5. Set C_2 and C_4 equal to zero, to force transverse symmetry.
6. Set the lateral and upper boundary conditions at infinity.
7. Evaluate the general solution by integrating over Ω_y and Ω_z with Fourier transforms. The expansion coefficients of these transforms are evaluated by *assuming* a profile for $Y(y)$ and $Z(z)$ at a specified x.
8. Choose Gaussian functions for these profiles. This choice takes advantage of a unique property of Fourier transforms, that the cosine transform of a Gaussian is a Gaussian also. [Other choices are possible, but most require solutions involving sums of infinite series.] Then *if* the real plume is a Gaussian at any x, it will be a Gaussian at all other x.
9. Evaluate k by conservation of mass.

The result of these assumptions and manipulations can be cast in several closely related ways. Perhaps most quoted of these [Turner, D.B., 1967] is:

$$C(x,y,z,h) = \frac{Q}{2\pi\sigma_y\sigma_z u}\left\{e^{\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]}\right\}\left\{e^{\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]} + e^{\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]}\right\} \qquad [7]$$

In [7] Q has a slightly different meaning from that in [1f]: here it refers to a total current [kg/s]; there it referred to a current per unit volume. H is a plume center-line height above the surface (at $z = 0$); x as before is a downwind distance from the source of Q; y is the transverse distance across the plume, and σ_y

and σ_y are dispersion lengths equal respectively to $\sqrt{2K_y x/u}$ and $\sqrt{2K_z x/u}$.

The coordinate z is measured upwards from the local surface, and the term in $z+H$ accounts for perfect reflection of the plume from that surface. Usually σ_y and σ_z are treated as empirical and are allowed to vary with other powers than $\sqrt{x/u}$, to account for the scale dependence of K_y and K_z.

A truly vast literature has evolved around theme and variations of equation [7]. Models are implemented with line- and area- sources for the Q's. Reflections from upper boundaries, as from inversion layers, have been included. Many parameterizations of the functional forms for σ_y and σ_z have been suggested and tested. Removal terms have been included for scavenging at the surface, or by chemical transformations in the plume, or by rain. Various schemes are proposed to mitigate against the otherwise embarrassing infinity that occurs when the wind speed, u, gets awkwardly small. Modifications of the Gaussian transform have been suggested as valuable in special cases, including 'cosine bells' and 'Bessel plumes'. Much discussion has been directed to proper averaging times, τ.

The train of approximations leading to Gaussian models is moderately severe. It should particularly be emphasized that Gaussian plumes are not *the* solution to [1f], but are instead *particular* solutions chosen for the considerable mathematical convenience that the functional form of the transverse concentration distributions is not a function of the downwind distance, x, which is indeed the case for all other solutions (and for real plumes). Gaussian solutions may be easily and rapidly computed. One considerable virtue of the Gaussian transform is that it is not affected by grid scales, and thus it eliminates numerical diffusion. One difficulty is that lateral and upper boundary conditions are awkward to modify for cases when cross-plume transport is inhibited by terrain or by upper inversions. Another is that the neglect of K_x is serious at low wind speeds. Let me now, however, delay a more complete discussion of the strengths and limitations of Gaussian models to later paragraphs, after first discussing an alternate approach to solutions of [1f] by more or less direct numerical integration.

C. 'Box' Models: Special Approximations

In contrast to transform solutions of [1f], direct numerical integrations involve detailed considerations of discrete spatial grids and finite time steps. The grids are 'boxes', and all finite-difference numerical integrations are loosely spoken of as 'box models'.

To simplify the following discussion, let me once again compress [1f] into one spatial dimension, x, and set up an array along that axis with steps of dimension δx, labeled by an integer index, i, increasing rightwards. With finite-difference arithmetic, the first and second spatial derivatives of C may be approximated as:

$$\frac{dC}{dx} \approx \frac{C_i - C_{i-1}}{\delta x} \qquad \text{and} \qquad \frac{d^2C}{dx^2} \approx \frac{C_{i+1} - 2C_i + C_{i-1}}{\delta x^2}$$

and the time derivative as:

$$\frac{dC_i}{dt} \approx \frac{C_i(t+\delta t) - C_i(t)}{\delta t}$$

These approximations become exact in the limit of δx and $\delta t \rightarrow 0$, but are inexact with finite grids, to the extent that

$$\frac{1}{C}\frac{d^{n+1}C}{d\xi^{n+1}}\delta\xi^{n+1} > 0 \quad ,$$

where ξ is δx or δt, and n is the order of the approximated derivative. Note that the approximation for the second derivative is 'centered' about C_i at x_i, but both the first derivatives are uncentered: that for x is 'backward', and that for t is 'forward'. We need the forward difference, of course, to move the solution forward in time, but choosing the backward difference for the first spatial derivative is an additional approximation that is useful in suppressing certain numerical instabilities.

Substituting the two spatial approximations into [1f], and rearranging, we get:

$$\frac{dC_i}{dt} = A - B\ C_i \qquad [1g]$$

where

$$A \equiv \left[\frac{u}{\delta x} + \frac{K_x}{\delta x^2}\right] C_{i-1} + \left[\frac{K_x}{\delta x^2}\right] C_{i+1} + Q_i$$

and

$$B = \left[\frac{u}{\delta x} + 2\frac{K_x}{\delta x^2} \right] .$$

If we chose, we might also substitute the finite difference for dC/dt and approximate a solution to [1g] as a first-order Euler expression of the form

$$C_i(t+\delta t) \approx C_i(t) + \left[A - B\ C_i(t) \right] \delta t \quad , \qquad [1h]$$

but a greatly improved approximation to [1g] is follows from an alternate, semi-analytical approach.

If in a short time step $\delta A/A$ and $\delta B/B$ are sufficiently small, then [1g] has an analytical solution

$$C_i(t+\delta t) = C_i(t) e^{-B\,\delta t} + \frac{A}{B}\left[1 - e^{-B\,\delta t} \right] \approx \frac{C_i(t) + A\,\delta t}{1 + B\,\delta t} \qquad [1i]$$

The generalization of [1g] and [1i] to three dimensions is straight forward:

1. Define indices j and k as parallel to the y and z axes.
2. Extend A to include

$$\frac{K_y}{\delta y^2}\left[C_{j+1} + C_{j-1} \right] + \frac{K_z}{\delta z^2}\left[C_{k+1} + C_{k-1} \right]$$

3. Extend B to include $2[K_y/\delta y^2 + K_z/\delta z^2]$.
4. Equations [1i] then hold with $C_{i,j,k}$ substituted for C_i.

Equations [1i] are special cases of a Gauss-Seidel relaxation. They are deceptively simple, but quite powerful. In the limit of $B\ \delta t < 1$ both forms converge to Euler's formula of [1h], and in the limit $B\ \delta t > 1$ they converge to the steady-state solutions $C(t+\infty) \approx A/B$. Numerical errors that stem from either version of [1i] compare very favorably with those of much more complicated and time consuming algorithms, including higher-order Taylor series and Runge-Kutta methods, and with implicit schemes such as Gear's method and various staggered-grid 'leap-frog' integrations. One not-inconsiderable advantage of [1i] is that it conserves mass strictly at all time steps; this is not automatic with all schemes.

To adapt [1i] ... or other 'box' algorithms ... to explicit problems is also straight forward.

1. Set up an x,y,z (*i.e.* i,j,k) grid with δx, δy, and δz
2. Set up boundary conditions at specified i,j,k.
3. Specify initial conditions for $C_{i,j,k}$ at $t = 0$. Put these into a temporary scratch array.
4. Specify $u_{i,j,k}$, $Q_{i,j,k}$,and K_x, K_y, and K_z, all of which may optionally be functions of time.
5. Choose a time step on the order of the smallest 1/B [when time-dependent solutions are required ... longer time steps are permitted when steady-state solutions, only, are sought], and march the $C_{i,j,k}$ forward by one time step. Then update the scratch array and iterate to step 3.

D. Some Comparisions between Gaussian and Box Models

We have so far explored the fundamental transport equation and its reduction through the exchange approximation into a form that can be integrated either by transform methods, as with Gaussian plumes, or by direct numerical methods, as in the discussion of the previous section. In the present section I shall expand briefly on comparisons between these two approaches, with emphasis on choosing one or the other as most useful for different types of problems.

Clearly, both the transform and direct methods employ a long string of approximations, some in common and some separately. Considerable rigor has been lost along the way towards practical algorithms. Arguments about relative merits of the two approaches aren't often useful, as each must ultimately be tested by comparison with real measurements.

Unfortunately, these tests are expensive and so far have largely been inadequate. Of the two approaches, Gaussian methods have thus far been more popular, and thus most tested. They are incorporated into several standard packages that are widely distributed by the US Environmental Protection Agency, and through the Clean Air Act and its various updates are to a certain extent written into federal law. Tests comparing hourly averages for predictions, with observations,

generally agree within a factor of two for 50% or more of independent cases, but with those cases generally selected for winds exceeding 1 m/s, and for generally flat terrain, usually for elevated sources. Gaussian models are easy to use, require only modest computational resources, and their familiarity to a wide user community enhances the clarity of communication between users applying them to disparate problems. Gaussian models are numerically stable and immune to numerical diffusion. They always conserve mass. By varying the transport parameters in stochastic ways that match real climates, Gaussian models may be used to estimate frequency distributions for pollution episodes, but for this type of study the practical restriction to winds exceeding 1 m/s weakens confidence in the models' predictions of what are often the most severe pollution events. Our greater experience with Gaussian models tends to reduce errors of misapplication, and to enhance confidence in their predictions for those most contentious cases that end in court.

On the otherhand, Gaussian models tend to have most trouble in exactly those cases when severe pollution episodes are most likely: with strong inversions, unstable flows, rapidly varying winds and stabilities, and especially in complex terrain, where the latteral boundary conditions of Gaussian models [usually at infinity] can be adapted to enclosing terrain only through awkward sums of infinite series of reflections, or through unsatisfying and *ad hoc* patches between discontinuously modeled domains.

In contrast, 'box' models have generally complementary defects and virtues. They tend to be written in *ad hoc* applications, one problem at a time. No standard box model is available from, or approved by, the federal machinery. They have been much less tested against real measurements. Box models are more demanding of computational resources, both of machine time and memory, and of programing skills and time. Numerical diffusion remains a problem, and solutions must be checked vigorously to assure both that gross programing errors have been eliminated and that solutions are insensitive to time steps and grid sizes.

Box models are inherently flexible. Boundary conditions can be handled in transparent and satisfying ways, so that these models are inherently more adaptable to complex terrain. Restrictions on the frequencies with which the transport

parameters may vary are less severe, and no restriction is imposed by minimum wind velocities. Thus box models engender more confidence when applied to estimates of worst cases, or to probabilities that measurements will exceed specified levels.

The choice between these two approaches, in the absence of clear guidance by comparing with real measurements, is therefore ... it seems to me ... partially a matter of taste (over which, after all, there can be no useful arguments) but partially also of resolving what questions are to be addressed of the models.

In my judgement:

1. For computing time-averaged pollutant concentrations in open terrain, and especially with smaller budgets and the overhang of possible litigation, go Gaussian.
2. For estimating worst cases, or in complex terrain, and with larger budgets, be boxy.

III. WYNDvalley, An Application of Box Modeling to the Methow, Chewack, and Twisp River Airshed of Okanogan County, Washington

The project described here was performed for the Okanogan County Planning Department, by R.W. Beck and Associates of Seattle, WA. A report describes this work, entitled 'METHOW VALLEY AIR QUALITY STUDY AND MANAGEMENT PLAN', of June 30, 1985, by Naydene Maykut (project manager), Mark Sadler, Lee Fortier, Karen Kerruish, Linda Kenney, Geralyne Rudolf, Ann Batson, Halstead Harrison, and James King. Portions of this report are reproduced here as Appendix I. Please consult this Appendix' Sections 1 and 2 for a general description of the project, a discussion of the ambient air-quality standards applicable to the modeled region, and a survey of the data and of the meteorology and climate.

Section 3 of Appendix I gives an overview of the model's selection and development, and Section 5 presents the modeled results. In a separate Appendix II are presented additional results for the resolution of carbon monoxide (CO) in the valley, sloshing north and south with the diurnal wind field and shown as a 'movie' of isopleth maps, at 6 hour intervals. These plots were not included in the principal report, for reasons of space. Appendix III documents a correspondence with Dr. D.G. Fox, of the Rocky Mountain Forest and Range Experimental Station at Fort Collins, Colorado, amplifying limitations of WYNDvalley that result from restriction to one layer and spatially uniform winds.

Please now read Appendices I and II. A discussion of Appendix III will be deferred to a later section of this present report.

In the section (A) that immediately follows, I shall amplify the material of Appendices I and II, describing the various pieces of the *WYNDvalley* program. In section (B) I shall discuss the choices of the transport parameters. In (C) I shall amplify upon the output, and in (D) I shall comment on various shortcomings of the model, and suggest some improvements.

A. The Model

The starting point for this effort was an earlier hybrid Gaussian-Box model written by D. Lamb for the Forest Service (Lamb, 1984). This effort modeled the Methow and Chewack valleys, with 14 boxes and a preliminary source inventory. The model's output suggested likely violations of total suspended particles (TSP) in the airshed, if plans were to mature for a ski resort in the upper Methow valley at Early Winters. This warning both suggested the need for a more detailed study and modulated the form that study might take: more boxes, a more detailed examination of plausible emissions, and re-examination of the governing meteorology.

With *WYNDvalley,* first questions were then addressed to spatial scales: how fine should be the horizontal grid? As part of the Methow project, emission data were summarized and projected by J.D. King and Associates, with 1 mile x 1 mile resolution. The characteristic spatial dimensions of the valley would be poorly resolved at this resolution, however; a early decision, then, was to model at half that scale for the spatial resolution, and to apportion emissions from each 1-square mile section into 1,2,3, or 4 quarter sections of a 1/2 x 1/2 mile grid, according to whether that number of quarter sections was contained in the perimeter of the modeled valley. Guided by Okanogan County's planning council, the modeled region was specified as extending from a bit north of Mazama in the upper Methow, to a valley foot 14 miles south of Twisp. The horizontal boundaries of the modeled area were drawn along the 2000 foot contour south of Winthrop, rising to 2400 feet in the upper Methow and Chewack valleys. This region encompassed 410 quarter sections.

An important second decision had to be made concerning the number of layers to be modeled [one] and whether the box heights should vary with position along the valley floor [no]. These calls were essentially arbitrary, but were governed by judgment on the effort/return ratios of other strategies. Some further discussion of these choices will be deferred to a later section of this report.

Next I chose the coordinates, which perhaps might most simply have been Cartesian. Owing to the long and narrow geometry of the modeled region, however, such a grid would be inefficient with computer memory. Consequently, each box of the irregular domain was assigned an address, and a 'connectivity matrix' was

written to couple each box the the addresses of the upvalley, downvalley, and transversely neighboring boxes. I began to do this by hand, working from contour maps, and starting from the upper Methow. About two hours later, near box 150 or so in the Winthrop basin, I started to find mistakes back at the 125th or so, and recognized that this was a losing game. I consequently wrote a triplet of preliminary programs to outline an arbitrary modeled area, to assign both Cartesian and sequential addresses to each box, to identify upvalley, downvalley and transversely neighboring boxes, and to write a general connectivity matrix. This effort amounts to a program to write another program. Thus *WYNDvalley* is in effect a 'higher' model, in the sense that FORTRAN is a 'higher' language. One wonders how many tiers of such abstractions we may encounter in the future.

The next step was to apportion the source inventories to each quarter section, both for TSP and for CO. In cooperation with Ms. Ann Batson of TTL, a 24 hour emission schedule was assigned to TSP from fireplace emissions, and three separate schedules were assigned to CO from fireplaces, cars, and a local airport. [Please see figure III-2 in Appendix I.] As described in a preceding paragraph, daily emissions tabulated by J.D. King were partitioned among the quarter sections; then at every hour during the simulation emissions were taken as proportional to these daily emissions times a normalized hourly fraction derived from the emission schedules.

Boundary conditions were set as 'reflective' at all the lateral edges of the valleys. That is, at the left edge the C_{i-1} for the box just to the left of the valley rim was set equal to the C_i for the box just to the right; similarly at the right edge C_{i+1} was set equal to C_i. At the southern boundary of the valley system the boundary condition was set as 'absorptive'; that is C_{j+1} was set equal to zero. At the upvalley edges of the Methow, Chewack, and Twisp boundaries were set as 'constant slope'; that is C_{j-1} was set equal to $2\ C_j - C_{j+1}$.

With choices for the winds and diffusivities [as discussed in the following section (B)], one may now proceed to crank out predictions of TSP or CO concentrations as functions of time, for incremental steps of ten minutes and with reporting intervals of six hours, for a period of three days, with zero-concentration initial conditions for all the boxes. Output was stored in a series of files, one for each

six-hour interval and one for the 24-hr average of the last modeled day. An additional file saved the local TSP or CO at three specified stations [usually near Early Winters, Winthrop, and Twisp], at every 10-minute interval over the three days. These files could be displayed graphically by two subsidiary programs.

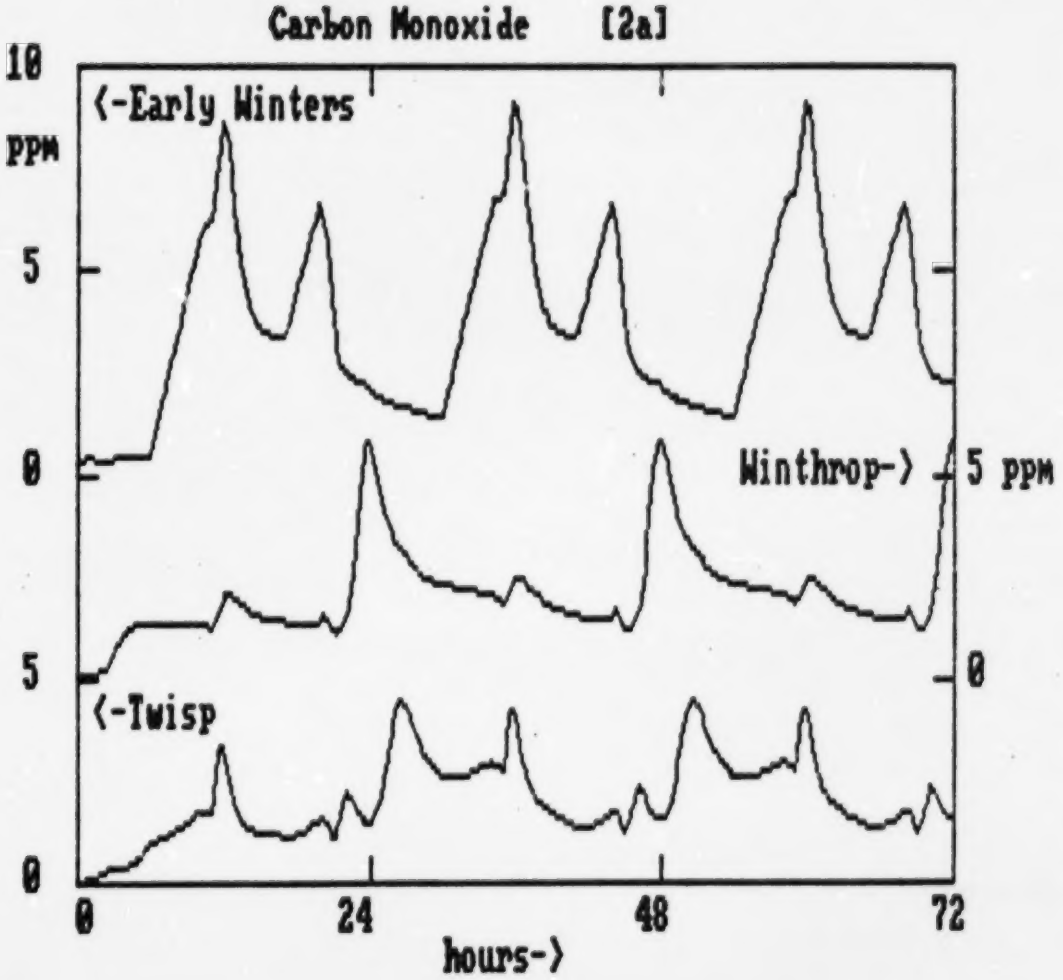
Examples of the 24-hour averaged fields are displayed in Appendix I as figures IV-4 (2a), IV-4 (2b), etc., corresponding to combinations of various source and control conjectures, as summarized in Appendix II, Table V-1. A sequential series of plots for the 6-hour intervals, for CO, are presented in Appendix II. An example of the temporal plots for CO is given in figure 2 of this report. Note in this last figure that the highest 8-hour average CO at Early Winters exceeds the highest 24-hour average by about 40%.

The storage of output in intermediate files permitted post-processing in various ways, especially by subtracting one output field from another, to display increments. Examples of such plots are given in Appendix I, figures V-5 (2a-3a), and so on. A second and informative post-processing exercise involved an intentional degradation of the spatial resolution for the several dozen boxes near Winthrop that had been represented in earlier simulations by a single larger box. This test showed vividly that it is easier to 'meet' 24-hour standards with big boxes than with small, if the latter contain hot-spots that average out in the former.

These calculations were all programmed in Microsoft BASICA, and were executed in compiled code using an XT-clone at 4.66 Mhz, with an 8087 math coprocessor chip. Execution times for a three day simulation were typically somewhat longer than two hours. Since these codes were written more efficient compilers have become available, as have inexpensive machines with higher clock rates. With both these advances computation speeds would be expected to increase by about a factor of four [1].

[1] With Microsoft QuickBasic version 3.0, compiled with the /q option for 8087 chips at 4.66 MHz, the 3-day simulation required 32 minutes, a speed-up factor of six. (6/14/87)

Figure 2


Carbon Monoxide [2a]
10
ppm
5
0
5
0
<-Early Winters
Winthrop->
5 ppm
0
<-Twisp
0
24
48
72
hours->

B. The Transport Coefficients.

In the previous section I outlined the sequence of choices leading to the selection of grid topology, size, and boundary conditions. In this section I amplify on the choices of box heights, the schedule of winds, and the horizontal and vertical diffusivities.

In the selection of box heights we were guided by a very useful study of Robinson and Boyle (1977), who monitored acoustic echoes from temperature discontinuities in the winter air above the valley floor near Winthrop. They reported strong inversions as frequent in winter, at heights varying between 50 and 300 meters. As we were interested in a 'semi-worst case', we chose 100 meters. Robinson and Boyle also report sonograms showing a 100 meter inversion lid that became progressively leaky between 10 AM and 5 PM, PST, but re-established itself strongly outside these winter hours. We therefore modulated the vertical ventilation coefficients during the leaky window, as described in later paragraphs of this section.

A serious question arose as to whether the box-heights should be modeled as uniform above the local surface, or uniform above sea level, or somewhere in between. A conversation with the local ranger revealed anecdotal evidence of winter occasions when 'the smoke wouldn't go up the chimney' at Mazama, near the head of the upper Methow River at contours near 2400 feet. If taken literally, this would imply a strong inversion right at the ground, and any model using a zero-height box would then predict infinite pollutant levels. It is clear that by choice of parameters the modeler may produce (or distort) output arbitrarily. Some judgment inevitably enters the parameter selection, and this makes difficult their rigorous defense. Guided in part by my instructions to model 'plausible semi-worst cases', and in part for model simplicity, I chose to keep the box heights uniformly 100 meters above the valley floor.

Wind measurements were taken for the winter of 1984-1985 by the USDA Forest Service, near Winthrop, in conjunction with TSP measurements by the Washington State Department of Ecology. In a 'semi-worst case' with overcast winter air, winds typically blew down the valley at 1.5 mph from about 5 AM through 10 AM, were essentially calm from 10 AM through 5 PM, blew upvalley at 1.0 mph

from 5 PM through 8 PM, and remained calm again until 5 AM. Please appreciate, however, that these winds and schedules are approximate. Figure III-1 of Appendix I illustrates this schedule for the ventilation and winds.

Some experimentation and 'fiddling' went into the selection of the horizontal diffusivities K_x and K_y, and a vertical ventilation coefficient, R_z. For a one-layer model, the vertical transport out the top of the boxes takes the form

$$\left[\frac{dC_{i,j}}{dt}\right]_{\text{ventilation}} = -R_z C_{i,j} \quad \text{with} \quad R_z = \frac{K_z}{\delta z^2}$$

In the absence of measurements for these transport parameters, one sensible route is to estimate them through the Gifford-Pasquill-Turner stability classes. The fundamental definition of diffusivities is:

$$K_\xi \equiv \frac{1}{2}\frac{d\sigma^2}{dt} = \sigma\left(\frac{d\sigma}{dx}\right)\left(\frac{dx}{dt}\right) = \sigma u\left(\frac{d\sigma}{dx}\right) = \left(\frac{\partial \ln\sigma}{\partial \ln X}\right) u\frac{\sigma^2}{x}$$

where ξ is either a transverse or vertical dimension, and σ is the root-mean-square separation of collections of dispersing particles, at downwind distance x, with wind speed u. Figures 3-2 and 3-3 of Turner's 'Workbook of Atmospheric Dispersion Estimates' (1967), reveal that

$$\left[\frac{\sigma_\xi(x)}{\sigma_\xi(X_o)}\right] \approx \left[\frac{x}{X_o}\right]^{\alpha_\xi}$$

where $\alpha_\xi = \partial \ln(\sigma_\xi)/\partial \ln(x)$. [The reader should be aware also of several updates of this classic workbook: Briggs et all (1977); Tikvart and Cox (1984).] In the preceeding equation X_o is a virtual distance that a hypothetical point plume would have to travel before developing a Gifford-Pasquill-Turner dispersion σ_y = 804 meters, the grid dimensions for the present model. For diffusion in the y coordinate α_y is essentially constant and equal to 0.91, but for vertical diffusion α_z is a function of X_o. Differentiating and substituting we get

$$K_{x,y} = \alpha_y u\frac{\sigma_y^2}{X_o} \quad K_z = \alpha_z u\frac{\sigma_z^2}{X_o} \quad \text{and} \quad R_z = \frac{\alpha_z u}{X_o} \quad R_{x,y} = \frac{K_{x,y}}{\delta x^2}$$

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SECTION I

SUMMARY

1. INTRODUCTION

Recent population growth and development in the Methow Valley and projected future growth resulting from development of a destination ski resort at Early Winters have raised concerns in Okanogan County regarding current and potential impacts on air quality. In order to identify potential impacts at an early enough stage to circumvent a decline in the Valley's air quality, the Okanogan County Planning Department undertook the development of an Air Quality Management Plan for the Methow Valley. The purpose of the plan is to guide the County in its efforts to deal effectively with existing and projected air quality problems resulting from accelerated growth and development. Particular attention should be given to projected air quality impacts resulting from the development of a major destination ski resort at Early Winters and other peripheral development.

The County Planning Department retained R. W. Beck and Associates to conduct the study and develop the Air Quality Management Plan. Elements of the study included an inventory and review of existing land use, demographic, economic, and census data affecting air quality within the Methow Valley study area. The study also involved forecasting contaminant concentrations, establishing planning goals, recommending implementation and management strategies, preparing a study draft report and final Air Quality Management Plan.

The following report documents the findings of the consultant study. Air quality data are presented in Section II, and air quality dispersion model selection and development are described in Section III. The input data for the model are described in Section IV, and the model results are presented in Section V. Planning goals and public input are discussed in Section VI. Relevant management strategies are presented and evaluated, and the

preferred air quality control strategies identified in Section VII. The Air Quality Management Plan and implementation strategies for the plan are presented in Section VIII.

2. STUDY PLAN

As described above, the Okanogan County Planning Department retained R. W. Beck and Associates to conduct an air quality study and develop an Air Quality Management Plan for the Methow Valley. A project team was assembled to provide expertise in all areas of concern for developing a detailed and useful plan. In conducting the study, the team:

- Developed a customized box diffusion model for the Methow Valley
- Assumed meteorological conditions reflecting past meteorological data and approximating realistic worst-case conditions
- Developed land use projections based on population figures from Social Impact Research, Inc.'s (SIR's) study and distribution patterns based on Okanogan County's 1983 study of analogous ski areas
- Developed emission factors for the major sources of carbon monoxide (CO) and total suspended particles (TSP) based on recent literature values and incorporating results from a recent survey of Okanogan County residents
- Ran the customized Methow Valley model for a variety of cases, including all combinations of "with" and "without" the Early Winters development and with and without the Draft 5 Proposed County Interim Ordinance (See Appendix F.)

- Ran the model for the incremental changes between the 1978 baseline year and the maximum buildout year of 2010 for the combinations described above to compare with the Preventions of Significant Deterioration (PSD) increments

3. RESULTS

The results of the modeling effort showed that the CO standard would not be exceeded by 2010 with or without the Early Winters development. However, the TSP standard and the PSD increment were exceeded in all cases for the year 2010 with or without the development and with or without the ordinance.

4. PLANNING GOALS

Public input from Methow Valley residents indicated that present Valley residents placed a high value on clean air. Most citizens attending the public meeting were interested not only in attaining the health standards but also in protecting the Valley from significant visibility degradation. Planning goals for the Air Quality Management Plan developed from the public meetings and agency input include:

- Health protection
- Visibility protection
- Minimizing hardship to present Valley residents
- Maximizing public acceptance
- Conserving wood supply
- Low management cost
- High strategy effectiveness

A number of wood smoke control strategies were evaluated using the planning goals. The most effective set of strategies emerging from this comparison were incorporated into the proposed Air Quality Management Plan.

5. AIR QUALITY MANAGEMENT PLAN

The Air Quality Management Plan, which would guarantee meeting the PSD increments and, at the same time, be most responsive to the present Valley citizen's planning goals, consists of the following strategies:

- Wood Smoke Control
  - Public Education
  - Weatherization
  - Limitation
  - Episode Curtailment
- Fugitive Dust Control
- Smoke Management for Prescribed Burning

6. IMPLEMENTATION

The Air Quality Management Plan would be most effectively implemented and administered through County and city ordinances similar to the Draft 5 Proposed County Interim Ordinance. The most commonly used enforcement vehicles are the city and County building codes. Elements of the implementation program include:

- County and City Air Quality Control Ordinances
  - Fugitive Dust Control
  - Episode Curtailment
- County and City Building Code
  - Wood Stove Limitation
  - Weatherization
- Public Education Programs in Cooperation with American Lung Association and Public Schools
- Smoke Management of Prescribed Fires - USDA Forest Service

SECTION II

BASELINE DATA

1. AIR QUALITY

a. Applicable Air Quality Regulations

The Air Quality Management Plan must address two important Federal and State air quality regulations: the National Ambient Air Quality Standards (NAAQS) and the PSD. The two regulations require different approaches, which are discussed separately below.

(1) National Ambient Air Quality Standards (NAAQS)

The NAAQS are designed to protect human health and welfare. The Federal and State ambient air quality standards shown in Table II-1 apply in all areas of the State of Washington. The annual standards are never to be exceeded; short-term standards (24 hours or less) are not to be exceeded more than once per year (except for the 1-hour sulfur dioxide standard which is not to be exceeded more than twice in any 7 consecutive days).

Only two pollutants, carbon monoxide (CO) and total suspended particles (TSP), have present and projected emissions of significant levels to be of concern for the proposed distination ski resort. These pollutants were identified as potentially significant during preparation of the USDA Forest Service EIS (1984). In previous impact studies (USDA Forest Service, 1984, and Wilson, 1984), the air quality levels resulting from the proposed resort for these two pollutants were estimated and compared to the most restrictive NAAQS. The effects of the proposed ski development on the 24-hour particulate standard and 1- and 8-hour CO standards were considered for the maximum build-out year 2010.

TABLE II-1

AMBIENT AIR QUALITY STANDARDS

Pollutant	NATIONAL Primary	NATIONAL Secondary	WASHINGTON State
Total Suspended Particles (ug/m^3)			
Annual Geometric Mean ...	75	60[a]	60
24-Hour Average	260 ug/m^3	150	150
Sulfur Oxides (SO_2)			
Annual Average	80 (0.3 ppm)		0.02 ppm
24-Hour Average	365 (0.14 ppm)		0.10 ppm
3-Hour Average		1300(0.50 ppm)	
1-Hour Average			0.40 ppm[b]
Carbon Monoxide			
8-Hour Average	10 mg/m^3(9 ppm)	10 mg/m^3(9 ppm)	10 mg/m^3(9 ppm)
1-Hour Average	40 mg/m^3(35ppm)	40 mg/m^3(35 ppm)	40 mg/m^3(35 ppm)
Photochemical Oxidants			
1-Hour Average	160(0.08 ppm)	160(0.08 ppm)	160(0.08 ppm)[c]
Nitrogen Dioxides			
Annual Average	100(0.05 ppm)	100(0.05 ppm)	100(0.05 ppm)
Hydrocarbons (Non-Methane)[d]			
3-Hour Average	160(0.24 ppm)	160(0.24 ppm)	160(0.24 ppm)[e]

NOTE:
Annual standards never to be exceeded; short-term standards not to be exceeded more than once per year unless noted.

ug/m^3 = micrograms per cubic meter
ppm = parts per million
mg/m^3 = milligrams per cubic meter

FOOTNOTES:
(a) - This is not a standard; rather it is to be used as a guide in assessing whether implementation plans will achieve the 24-hour standard.
(b) - 0.25 ppm not to be exceeded more than two times in any 7 consecutive days.
(c) - Applies only 10 a.m. - 4 p.m. PST from April 1 through October 31.
(d) - This is not a standard; rather it is to be used as a guide in devising implementation plans to achieve the oxidant standard.
(e) - Applies only 6 a.m. - 9 a.m. PST from April 1 through October 31.

(2) Prevention of Significant Deterioration (PSD)

PSD regulations apply to areas having air of better quality than required by the NAAQS. PSD regulations are only applied to control TSP and sulfur dioxide (SO_2). In these clean-air areas, the air quality is only allowed to deteriorate a small amount. The amount of degradation allowed is known as an increment. Three increment levels have been established based on the three PSD air quality classifications: Classes I, II, and III. All Federal national parks or wilderness areas are Class I areas, and the air quality is carefully protected. All other areas, such as the Methow Valley, were designated Class II. Air in Class II areas is allowed to degrade slightly more than in Class I areas. No Class III areas were designated (Clean Air Act Amendments, 1977). Higher pollution levels are allowed in Class III areas; however, Class III areas are only established through a redesignation procedure. Only states and Indian-governing bodies can redesignate the PSD status of portions within their boundaries. PSD increments for each class designation are shown in Table II-2.

TABLE II-2

PSD INCREMENTS

Pollutant	Increment (ug/m^3) Class I	Class II	Class III
Total Suspended Particles:			
24-Hour	10	37	75
Annual Geometric Mean	15	19	37
Sulfur Dioxide (SO_2):			
3-Hour	25	512	700
24-Hour	5	91	182
Annual Mean	2	20	40

Increments for SO_2 are shown in Table III-2; however, the amount of this pollutant resulting from the proposed Early Winters development would be negligible. There are no PSD increments for CO.

The particle levels in a baseline year are compared to the levels in a future year to determine whether the allowed increment is exceeded. The baseline year is established by Air Quality Control Region (AQCR) in Washington. The baseline year for an AQCR is the year the first complete PSD application for a new or modified source within the AQCR is submitted. Each AQCR has a baseline year for each of the two PSD pollutants, TSP and sulfur dioxide. The TSP baseline year for Okanogan County is 1978, and was triggered by the completed Boise Cascade facility PSD application submitted August 3, 1978.

Emissions for the baseline year were determined by simulating conditions existing in the Methow Valley during the PSD baseline year of 1978. Emissions for the maximum buildout year, 2010, for the designation ski resort were estimated. These two results were compared to estimate the net change of air pollution concentrations in the Valley.

b. Air Quality Data

Limited air quality data are available for the Methow Valley. TSP monitoring was conducted in Mazama from February 1975 through July 1977, and in Winthrop from April 1975 through June 1977. Data obtained in these efforts showed December and January 24-hour average TSP levels of 2-15 ug/m^3 (Mazama) and 7-86 ug/m^3 (Winthrop). Annual geometric mean TSP concentrations ranged from 13-18 ug/m^3 in Mazama to 25-35 ug/m^3 in Winthrop. Peak 24-hour average data were recorded in the fall and ranged from 156 ug/m^3 in Mazama to 113 ug/m^3 in Winthrop. The maximum values for both Mazama and Winthrop occurred the same day, October 15, 1976, which was noted as a windy day. The second highest measurements from this monitoring era were 96 ug/m^3 in Mazama and 104 ug/m^3 in Winthrop.

The WDOE is presently conducting TSP monitoring in one location in the Methow Valley. This monitoring effort was initiated in December 1984. The sampler is located near Carlton on the southern edge of the study area. The maximum value during the December 1984 through March 1985 period was 45 ug/m^3 and occurred on January 1, 1985 (WDOE, 1985).

No other air quality data are reported for the study area.

2. METEOROLOGY AND CLIMATE

The meteorological data base consists of results of impact studies for the recreational development at Early Winters. Studies performed include a meteorological (wind speed and direction) comparison at two locations in the Methow Valley conducted by the WDOE concurrent with the December 1984 to January 1985 TSP monitoring (WDOE, 1985), a qualitative study reported by the USDA Forest Service in the Environmental Impact Statement (EIS) for the proposed Early Winters Alpine Winter Sports Area (USDA Forest Service, 1984) involving photographs and visual observations, and studies by Robinson and Boyle (1977) of meteorological and dispersion-related data for the Valley. The WDOE study

is of a more limited time frame, and was not used in this study. The Robinson and Boyle study in the winter of 1976 and 1977 is an analysis based on measured wind speed and direction, the temperature at three locations near the destination ski resort development site, and atmospheric stability measurements taken using an acoustic sounder. Results of the Robinson and Boyle study are used in this study to estimate the dispersion characteristics of the study area.

The Robinson and Boyle data indicate that a frequent surface inversion layer formed in the Valley and went through several lifting and reforming cycles during the day. The apparent reason for the variability in the height of the surface layer is the rough mountain valley topography, with cold drainage flow into the main Methow Valley from Early Winters canyon and the steep valley sides. Robinson and Boyle's interpretation of the data is that moderate mixing exists throughout the lowest 100 meters of the atmosphere. Robinson and Boyle further state that, in terms of Pasquill stability types, Type C (weak or light turbulence) during daytime and Types E and D (slightly stable or neutral) dispersion conditions can be considered average conditions for the surface layer. Robinson and Boyle conclude that persistent, highly stable periods are uncommon and likely to be accompanied by mixing heights of 150 meters or more. Average wind speeds were found to be low, with a median daytime speed of 2 mph and average nighttime speed of 1 mph at Shafer Field. Robinson and Boyle conclude that a mixing depth of 200 m could be used as a generally conservative value for daytime conditions, with wind flow up and down valley during daytime and nighttime periods, and wind speeds of 2 mph for daytime winds and 1 mph for nighttime.

The visual observation and photography study reported in the USDA Forest Service EIS provides data that correspond to results of the Robinson study. The visible haze layer observed is indicative of the mixing height of the inversion layer reported by Robinson and Boyle of 150-200 meters. The visual observation citings were often in mid-afternoon, which constitute evidence of persisting stable atmospheric conditions. The EIS reports, based on temperature data, that moderately severe inversion episodes could occur three to four times per year, each lasting 4 to 6 days.

Climate information is necessary to determine wood consumption and weatherization needs. The U.S. Weather Bureau and the Cooperative Extension Service (WSU, 1965) reported temperature and precipitation data for the 30-year period of 1931 to 1960 at Winthrop. Heating degree values used to estimate wood consumption were from this report.

Appendix I Section 3

Model Selection and Development

terrain-caused mechanical turbulence and wide canyon drainage both tend to increase dilution. The approaches used for up- and down-valley flows may not be representative of the most stable, cold weather conditions.

The model used in this study was specifically developed by Dr. Halstead Harrison for determining impacts in the Methow Valley drainage area. The model input values and the modeling approach have been approved by the EPA Region X. The model was used to estimate impacts for a pre-development base year, the impacts for the proposed development, and to determine the effectiveness of the Draft 5 Proposed County Interim Ordinance to ensure the PSD Class II TSP air quality increment is not exceeded.

The model developed is a box model which assumes uniform emissions within each box. Specific model assumptions are:

- The horizontal spatial resolution was 0.5 mile, or the box size was one-quarter section.

- Valley channels were taken as approximately within the 2,400-foot contours at the heads of the valleys, broadening to the 2,000-foot contours at Winthrop and Twisp, and with a valley foot about 14 miles south of Twisp (in Township-Range-Section 31-22-22).

- A "plausible semi-worst case" was postulated, for which:

  - An inversion lid was assumed to be 100 meters above the local valley floor

  - Up- and down-valley winds between +1.0 mph and -1.5 mph (up-valley winds assigned positive values; down-valley winds negative) were assumed, with ventilation rates of 0.08 hr^{-1}

and 0.25 hr^{-1} through the inversion lid. The wind and ventilation diurnal time schedule is illustrated in Figure III-1. These ventilation rates correspond roughly to the Gifford-Pasquill-Turner classifications B-C, and C-D, respectively (Figure III-1).

-- Diffusive cross-, up-, and down-valley eddy coefficients were parameterized as equal to the grid scale (0.5 mile) times one-half the magnitudes of the up- and down-valley winds, plus 0.5 mph (Figure III-1).

-- Emissions from cars, wood stoves, and aircraft were apportioned to each of the 409 spatial box elements, with diurnal emission schedules as illustrated in Figure III-2.

-- The model's boundary conditions were taken as reflective at the valley sides, constant gradient at the valley heads, and absorptive at the southernmost valley foot.

-- The model was run for three simulated days, starting from a clear-air start, with time steps varying between 10 and 15 minutes.

The meteorological assumptions used in modeling correspond approximately to postulated worst-case episodes occurring nearly 10 times per winter as described by Robinson and Boyle (1977).

Emission inputs to the model are based on expected land use patterns and air pollutant emissions. These are presented in Section IV.

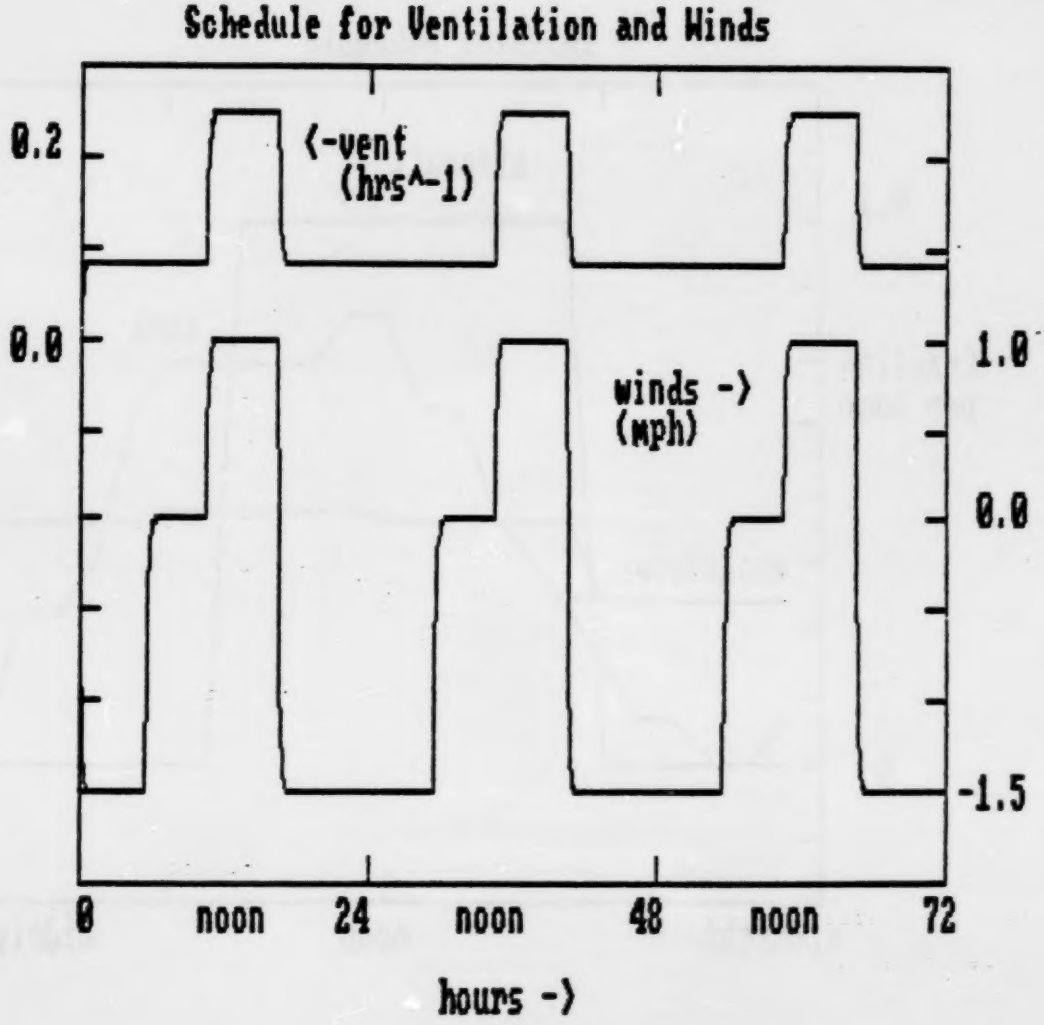

Schedule for Ventilation and Winds
0.2
0.0
<-vent
(hrs^-1)
winds ->
(mph)
1.0
0.0
-1.5
0
noon
24
noon
48
noon
72
hours ->

Figure III-1

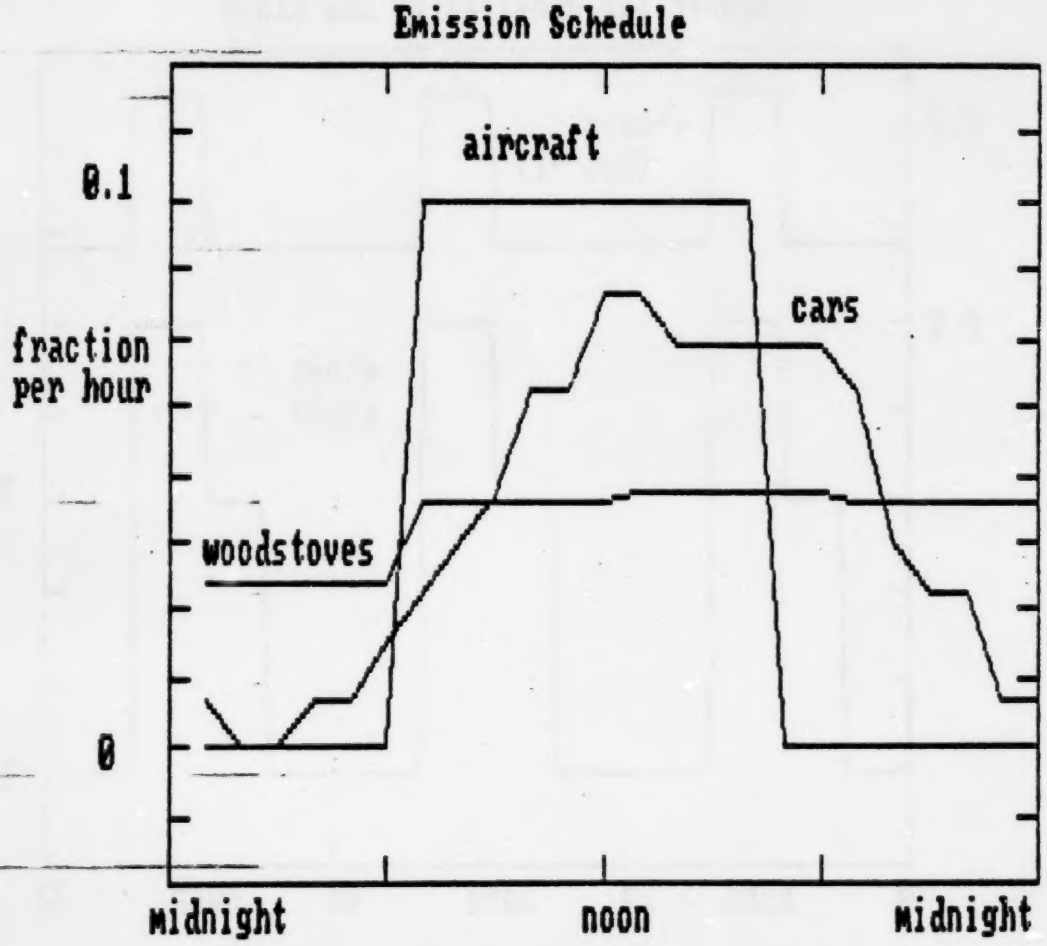

Emission Schedule
aircraft
0.1
cars
fraction
per hour
woodstoves
0
midnight
noon
midnight

Figure III-2

Appendix I Section 5

Model Results

SECTION V

MODEL RESULTS

As identified previously in this report, the two pollutants of concern for the Methow Valley are CO and TSP. The level of these pollutants present must not exceed the NAAQS. (See Table V-1.) In addition, TSP is covered by PSD regulations, requiring that the increment, which is an allowable increase in TSP levels, never be exceeded. (See Table V-2.) The PSD increment is more limiting than the NAAQS since the air will only be allowed to be degraded 37 ug/m^3 in any 24-hour period, while the NAAQS 24-hour standard is 150 ug/m^3. Concentrations for TSP must be estimated for a baseline year using the emission levels occurring during this year. These results are than compared to modeling results of projected maximum project buildout impacts. The net increase in estimated TSP concentrations from the baseline year to the maximum emission year for the development must be equal to or below the allowable increment.

Modeling was performed for both TSP and CO. For the modeling runs, maximum project emissions were estimated for the year 2010. The baseline year used for TSP emissions was 1978.

The ventilation and wind schedules used for all model runs are shown in Figure III-1. Peak wind speeds are at mid-day, rapidly decreasing by early afternoon and remaining low until mid-morning. The modeled daily emissions schedule are as shown in Figure III-2. Wood stove use remains fairly constant until very early morning; vehicle emissions peak at noon, remain high until late afternoon, and decline to the daily low after the bars close; and aircraft emissions were modeled as constant between 8 a.m. and 4 p.m.

1. CASE DESCRIPTIONS

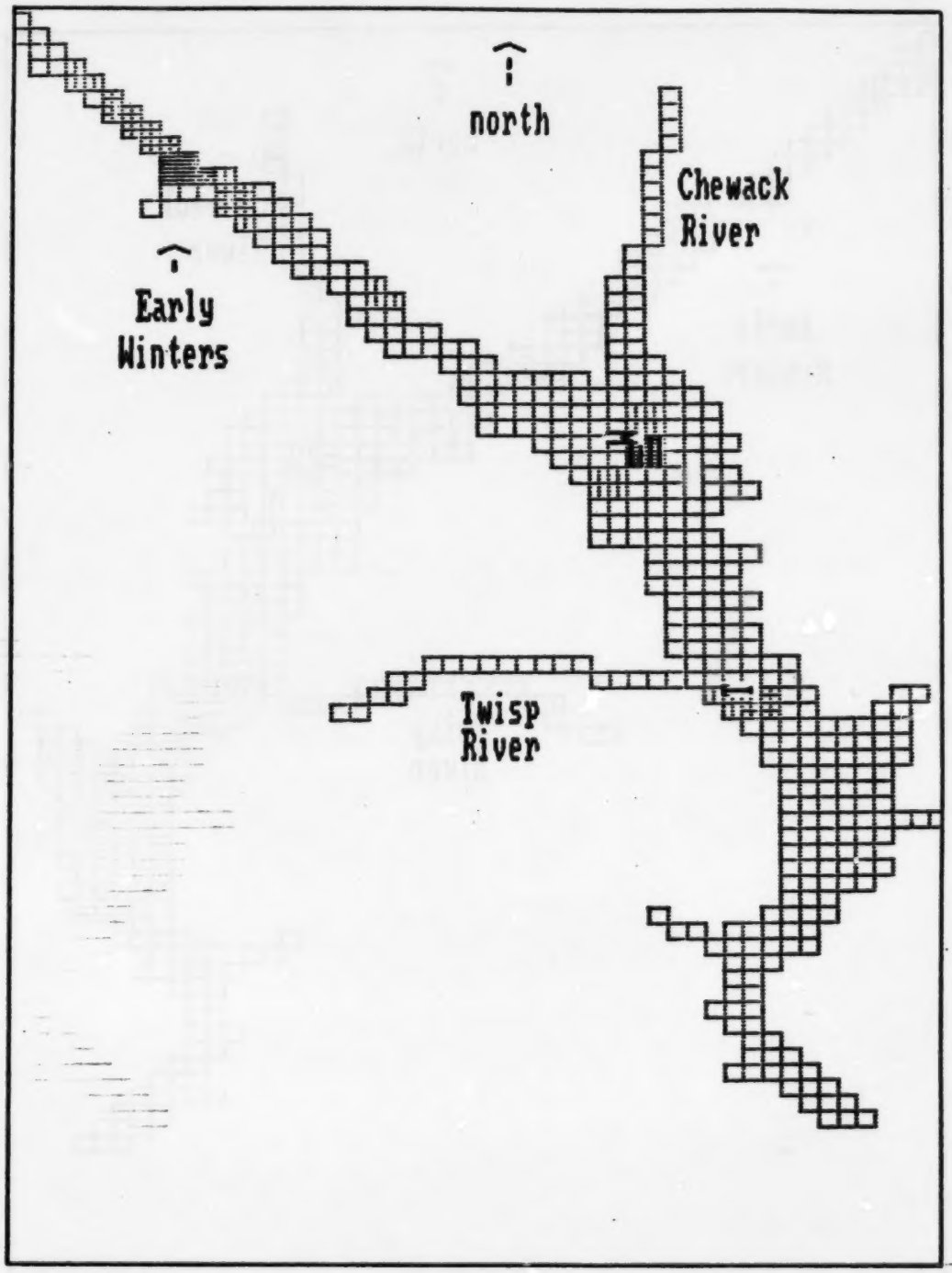
Four principal modeling scenarios were examined to determine CO and TSP impacts. Case 1 (a and b) estimated the CO impacts in the year 2010 with and without the destination ski resort, both assuming no control ordinance.

Case 2 (a and b) was a similar examination for TSP -- year 2010, with and without the resort and no control ordinance. Case 3 (a and b) examined TSP levels for a baseline year, 1978, and for 1985 to determine increased impacts to-date in the study area. Case 4 (a, b, and c) looked at year 2010 with and without the resort with a control ordinance.

The model predictions for all of the case runs depend on the input factors of the spatial distribution and quantity of emissions. The land use and emissions analyses resulted in emission density maps for each case which were used as input conditions for the model. The emission density maps for the six different scenarios for the TSP emissions are shown in Figure V-1 (2a) to Figure V-1 (4b). (NOTE: The case numbers are presented in ( ) for the figures in this section. The cases are defined in Table V-1.)

Results from the modeling runs including case type, pollutant, project development and control status, and peak concentration value and peak concentration location are shown in Table V-1. All model results are shown in concentration density maps (Figure V-2 (1a) to Figure V-10). The case type descriptions are presented in the following paragraphs.

Case 1 is for CO for year 2010 with and without the proposed destination ski report. Case 1a, with the destination ski resort, shows a 24-hour maximum impact of 4.8 ppm, compared to Case 1b, year 2010 without the resort, with a predicted maximum 24-hour levels of 2.0 ppm. For CO, the Federal standards specify 8-hour averages, rather than 24. Because the phase angles of the maximum 8-hour average vary widely throughout the map, the highest 8-hour averages were not calculated at every point. However, the time-resolved concentrations at three critical points on the map -- near Early Winters, Winthrop, and Twisp -- are plotted in Figure V-3, where it can be seen that the highest 8-hour average is about 20% higher than the 24-hour average at Early Winters, about 30% at Winthrop, and about 20% at Twisp. Thus, the highest predicted 8-hour CO averages are about 5.8 ppm for Case 1a and 2.5 ppm for Case 1b. The maximum 8-hour CO concentrations occurred near the proposed destination ski resort site.

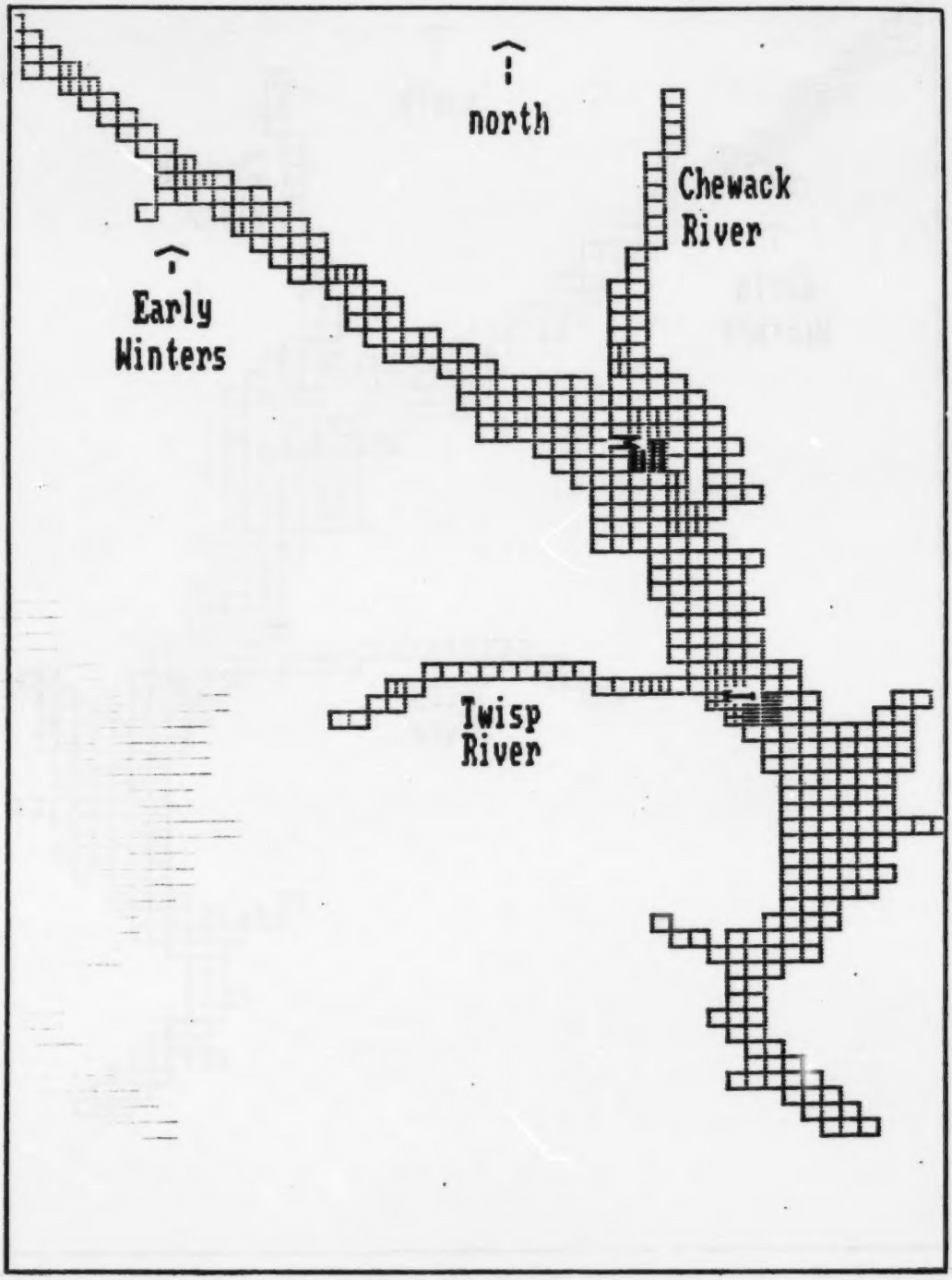


METHOW VALLEY AIR-QUALITY SIMULATION

1.51E+05 <	■	< 1.88E+05
1.13E+05 <	▦	< 1.51E+05
7.54E+04 <	⊞	< 1.13E+05
3.77E+04 <	⊟	< 7.54E+04
0.00E+00 <	□	< 3.77E+04 gm/day

TSP Emissions [2a]

Figure V-1 (2a)



METHOW VALLEY AIR-QUALITY SIMULATION

1.03E+05 <	■	< 1.29E+05
7.73E+04 <	■	< 1.03E+05
5.15E+04 <	⊞	< 7.73E+04
2.58E+04 <	⊟	< 5.15E+04
0.00E+00 <	□	< 2.58E+04 gm/day

Figure V-1 (2b)

TSP Emissions [2b]

2. RESULTS

The maximum predicted increment usage exceeds the 24-hour PSD Class II increment for TSP of 37 ug/m^3 for all cases. Model results indicate that for all cases studied, with or without the destination ski resort, and even with the Draft 5 Proposed County Interim Ordinance, further control strategies are likely to be needed to meet the TSP 24-hour PSD increment. The PSD program is designed to set an upper limit on the allowable degradation of air quality.

There are uncertainties inherent in all diffusion models, and additional uncertainties in model input assumptions. Results of these uncertainties can cumulatively approach a factor of 2. If the assumptions are more conservative than actual conditions, then model results are likely to be overpredicted. However, the uncertainties in the predicted increment values should be considerably less than those for predicted pollution values. This occurs because some of the errors in estimates will cancel when the values are subtracted.

Overall, pollution levels predicted by this modeling exercise are similar to those predicted by other studies. Wilson (1984) estimated maximum TSP concentrations near 400 ug/m^3. A recently completed thesis on the air quality in the Methow Valley by Grotheer (1985) predicted maximum of 350 ug/m^3. Grotheer's results were for year 2000 and assumed no control. Neither Wilson nor Grotheer had access to the emission density information that was available to this present study.

The results of the increment usage (Cases 4a-3a through 2b-3a) are shown in Table V-2. The increment consumed by each case is also compared to the allowable PSD increment in Table V-2. For all cases the net gain of pollutant exceeds the amount allowable, indicating that changes in the control strategies are required. Likely, a stricter degree of control measures than the Draft 5 Proposed County Interim Ordinance will be needed to meet the Class II increments. Additional control strategies are presented, evaluated, and discussed, in Section VII.

TABLE V-1

MODEL RESULTS

Case	Year	Pollutant	Early Winters	Control Ordinance	Highest 24-hr Avg.	Location of peak(s)
1a	2010	CO	With	Without	4.8 ppm	ew
1b	2010	CO	Without	Without	2.0 ppm	ew ww tt
2a	2010	TSP	With	Without	539 ug/m^3	ew ww
2b	2010	TSP	Without	Without	332 ug/m^3	ew ww tt
3a	1978	TSP	Without	Without	197 ug/m^3	ww tt
3b	1985	TSP	Without	Without	157 ug/m^3	ew ww tt
4a	2010	TSP	With	With	225 ug/m^3	ew ww tt
4b	2010	TSP	Without	With	195 ug/m^3	ew ww tt
4c	2010	TSP	*		181 ug/m^3	ew ww tt
4a-3a	—	TSP	—	—	125 ug/m^3	ew
4b-3a	—	TSP	—	—	64 ug/m^3	ew ww
4c-3a	—	TSP	—	—	63 ug/m^3	ww
2a-3a	—	TSP	—	—	489 ug/m^3	ew
2b-3a	—	TSP	—	—	219 ug/m^3	ew ww

CO and TSP refer to Carbon Monoxide and Total Suspended Particles.

The units (ug/m^3, ppm) are micrograms per cubic meter and parts per million, by volume.

The locations (ew, ww, and tt) refer to the upper Methow Valley near the proposed Early Winters site, near Winthrop, and near Twisp.

* Case 4c assumes the same emissions from the northwestern boundary of Winthrop south to Carlton as 4a; emissions in the upper Methow Valley are held to 1985 levels.

It should be emphasized that the last five entries are increments.

TABLE V-2

MODEL RESULTS YEAR 2010
VS. 24-HOUR PSD CLASS II INCREMENT

Case	Early Winters	TSP Central Ordinance	Highest 24-hr Increment	PSD Increment	Amount Exceeding Increment
4a-3a	With	With	125	37	88
4b-3a	Without	With	64	37	27
4c-3a	*	*	63	37	26
2a-3a	With	Without	489	37	452
2b-3a	Without	Without	219	37	182

* 4c - Ordinance applies to Winthrop south; no gain of emissions northwest of Winthrop from 1985 levels. Results for year 2010.

Appendix II

Additional Results: Temporal Behaviour of Carbon Monoxide

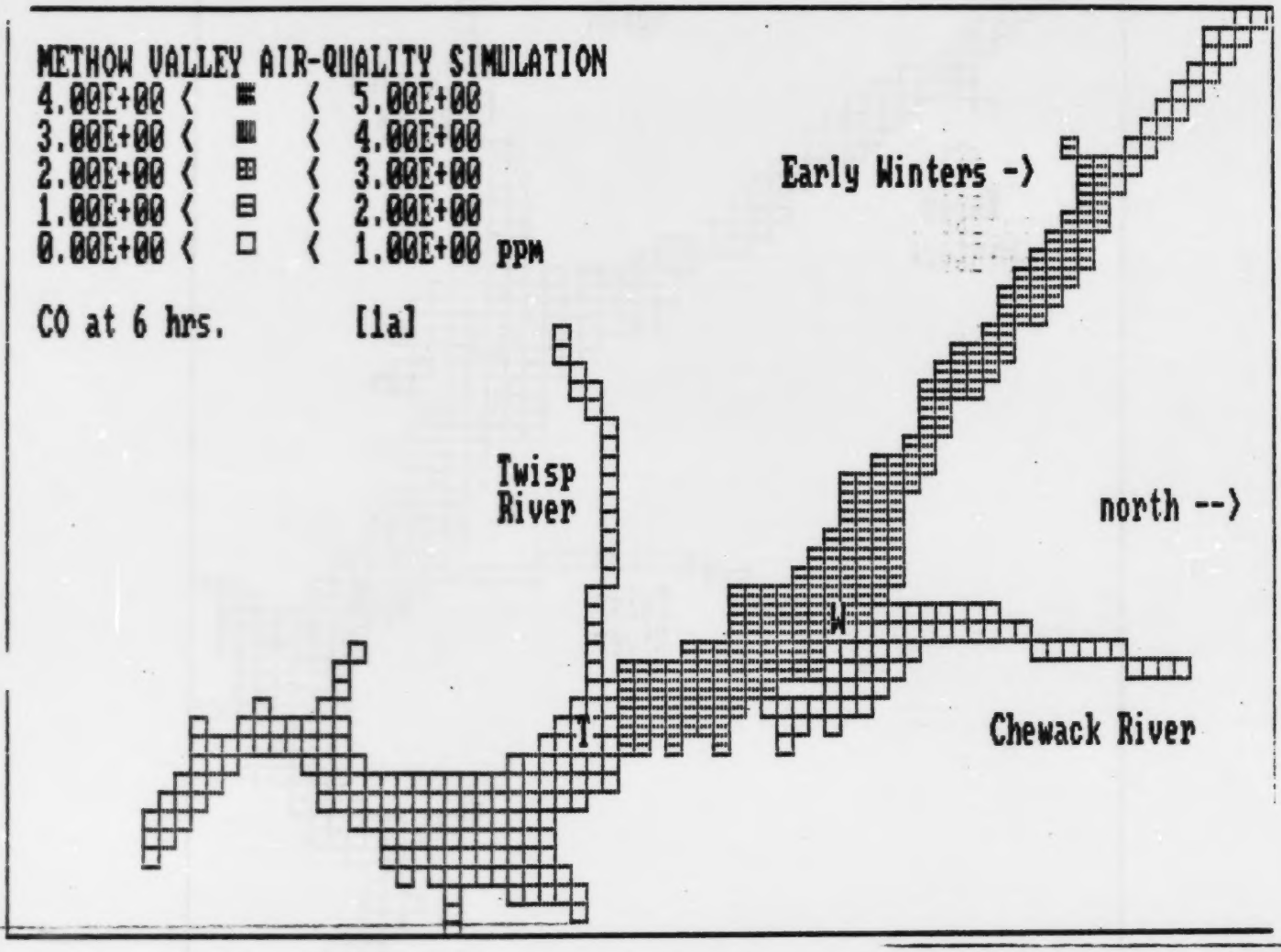
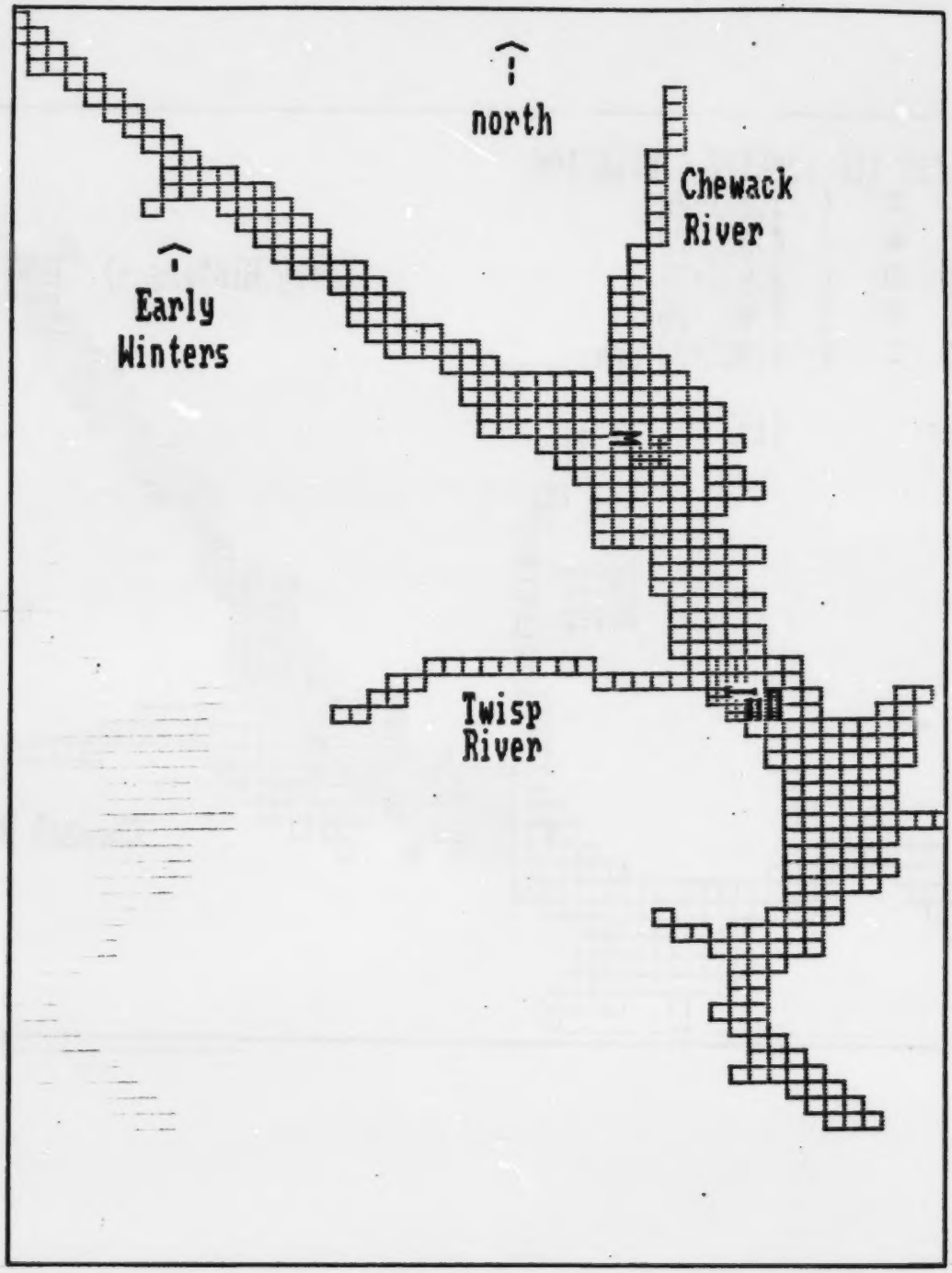

METHOW VALLEY AIR-QUALITY SIMULATION
4.00E+00 < < 5.00E+00
3.00E+00 < < 4.00E+00
2.00E+00 < < 3.00E+00
1.00E+00 < < 2.00E+00
0.00E+00 < < 1.00E+00 ppm
CO at 6 hrs. [1a]
Early Winters ->
Twisp River
north -->
W
T
Chewack River

Figure 9.06

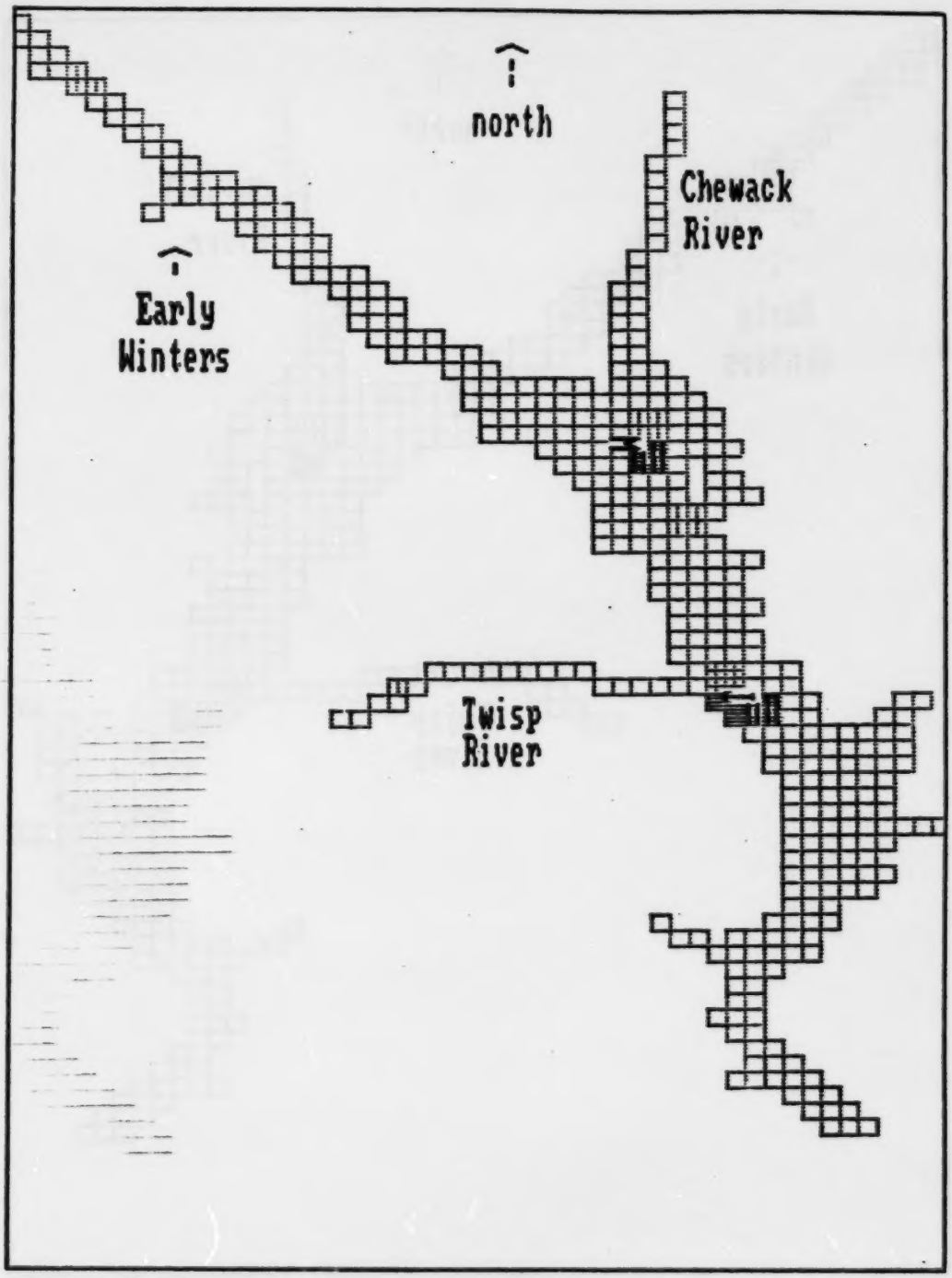


METHOW VALLEY AIR-QUALITY SIMULATION

7.29E+04 <	■	<	9.11E+04
5.46E+04 <	▥	<	7.29E+04
3.64E+04 <	⊞	<	5.46E+04
1.82E+04 <	⊟	<	3.64E+04
0.00E+00 <	□	<	1.82E+04 gm/day

TSP Emissions [3a]

Figure V-1 (3a)

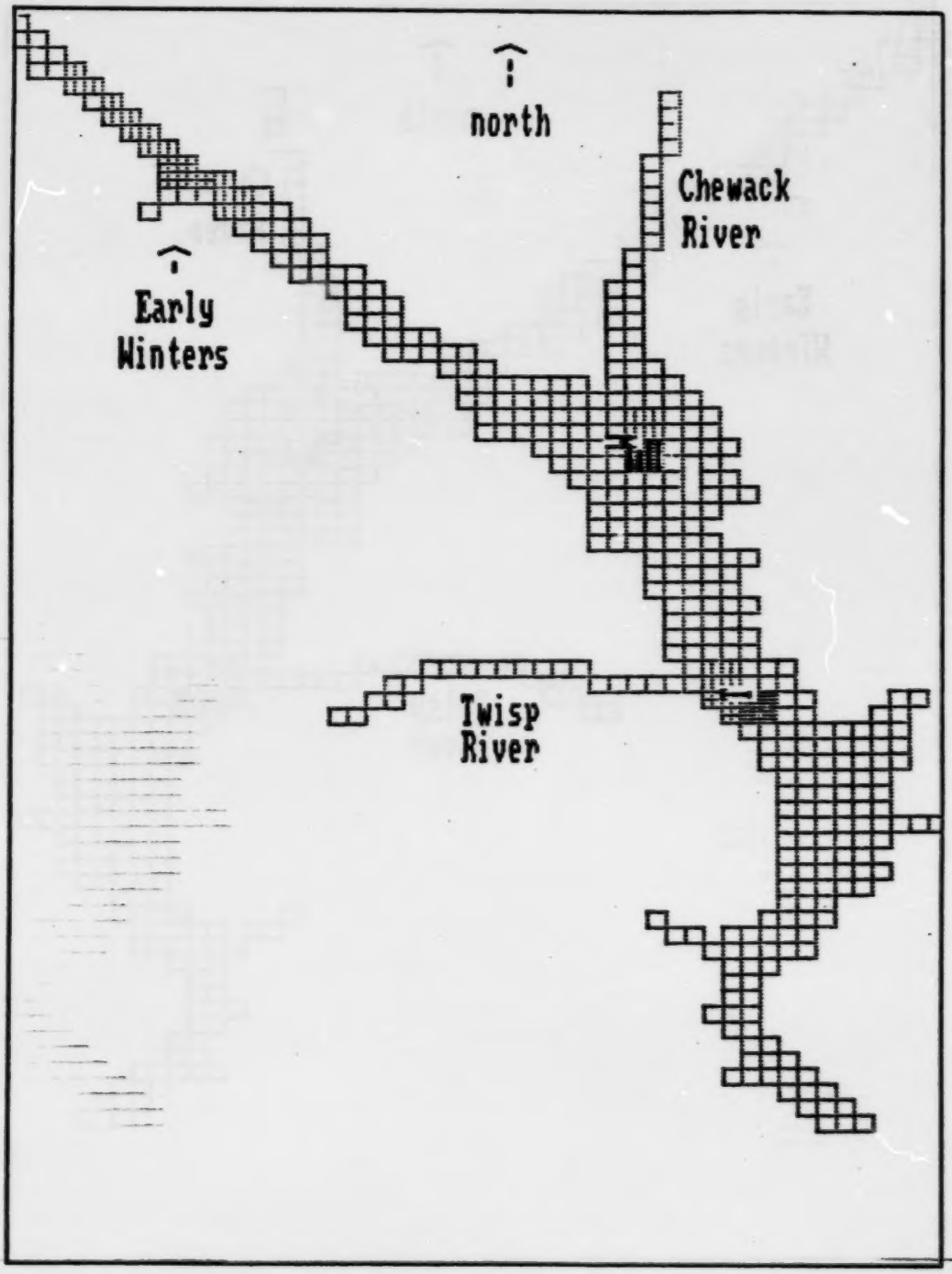


METHOW VALLEY AIR-QUALITY SIMULATION

4.48E+04 <	■	< 5.60E+04
3.36E+04 <	▩	< 4.48E+04
2.24E+04 <	⊞	< 3.36E+04
1.12E+04 <	⊟	< 2.24E+04
0.00E+00 <	□	< 1.12E+04 gm/day

Figure V-1 (3b)

TSP Emissions [3b]

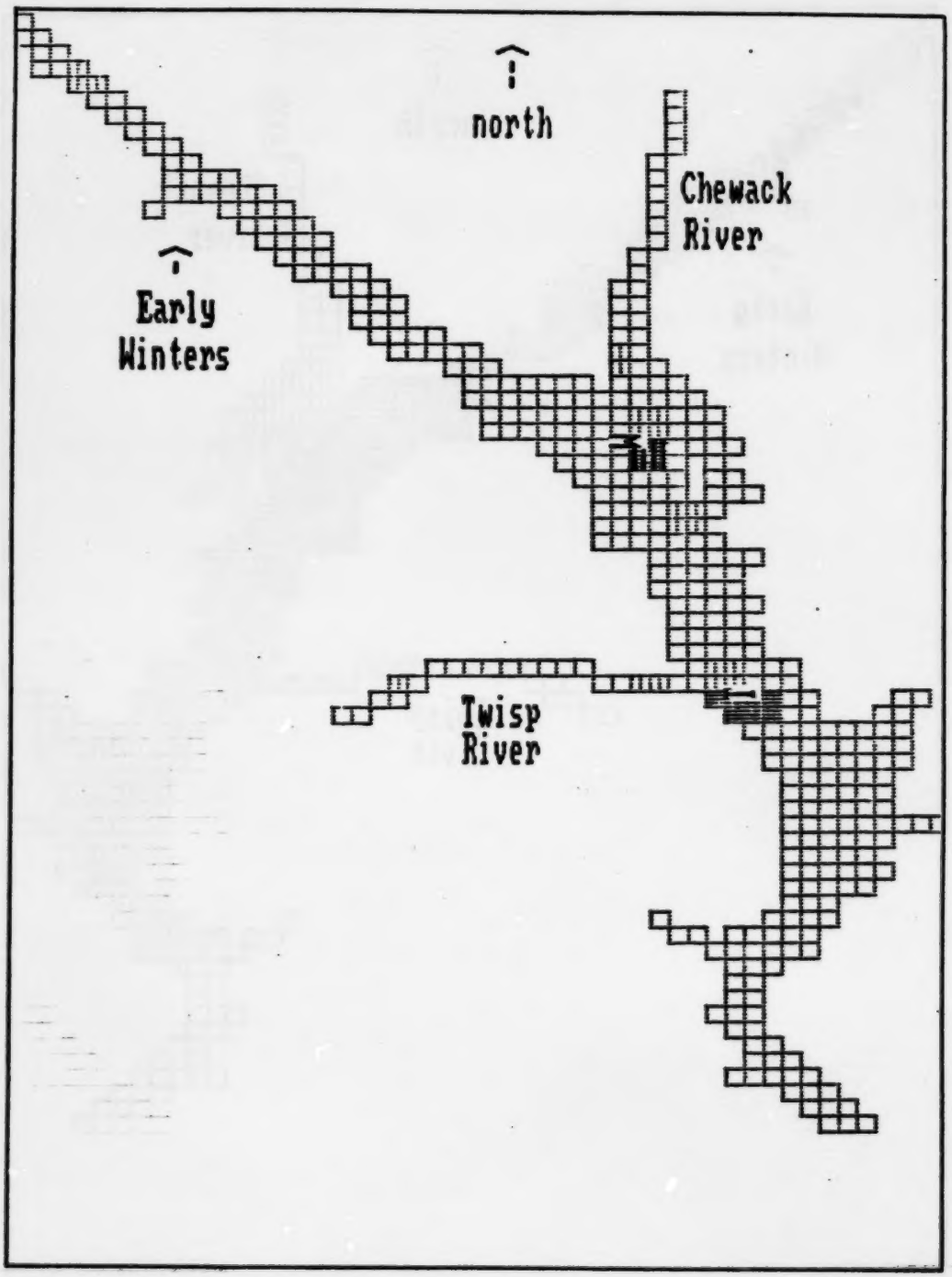


METHOW VALLEY AIR-QUALITY SIMULATION

7.13E+04 <	■	< 8.91E+04
5.35E+04 <	■	< 7.13E+04
3.56E+04 <	⊞	< 5.35E+04
1.78E+04 <	⊟	< 3.56E+04
0.00E+00 <	□	< 1.78E+04 gm/day

Figure V-1 (4a)

TSP Emissions [4a]

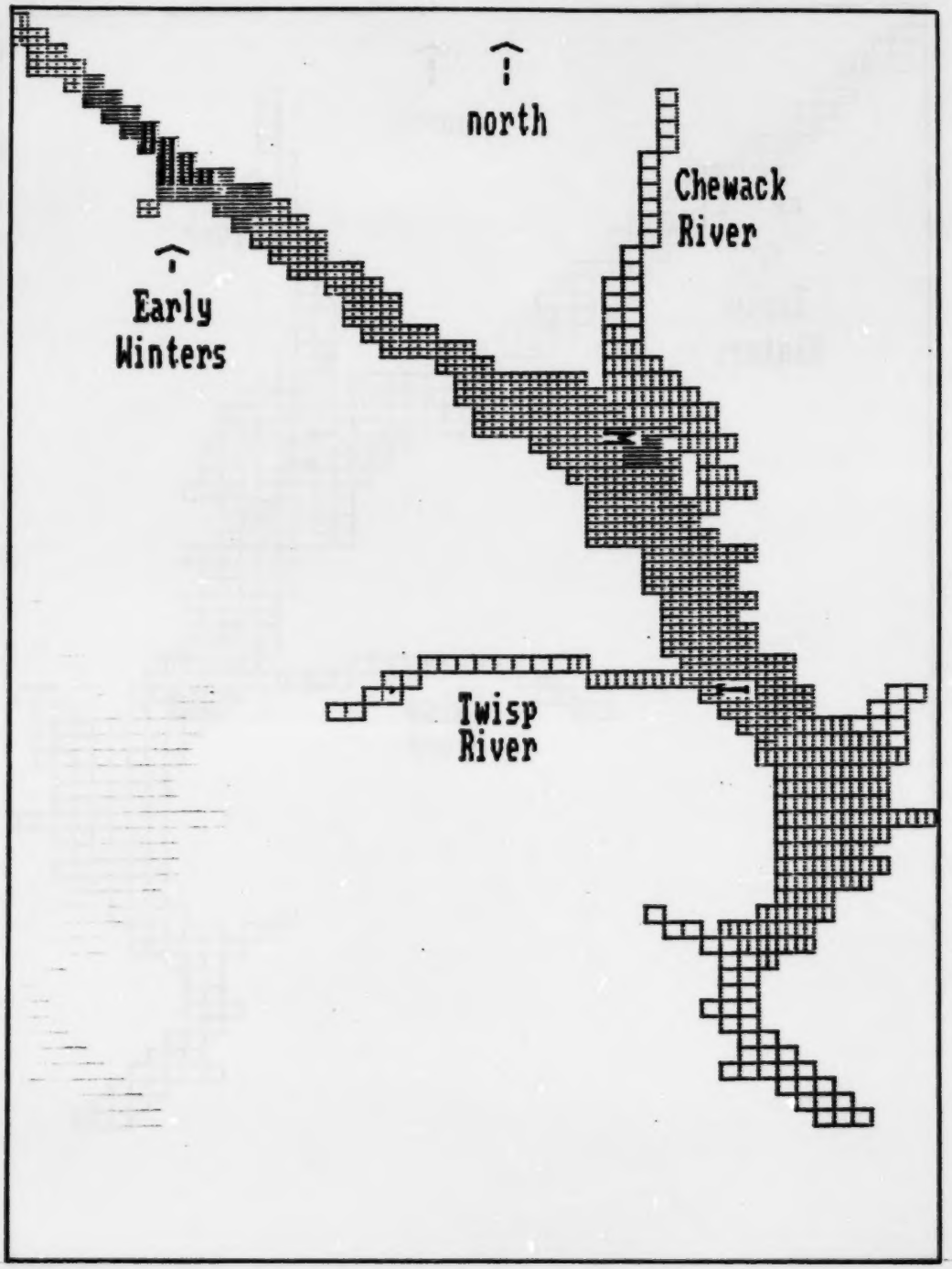


METHOW VALLEY AIR-QUALITY SIMULATION

5.95E+04	<	<	7.43E+04
4.46E+04	<	<	5.95E+04
2.97E+04	<	<	4.46E+04
1.49E+04	<	<	2.97E+04
0.00E+00	<	<	1.49E+04 gm/day

Figure V-1 (4b)

TSP Emissions [4b]

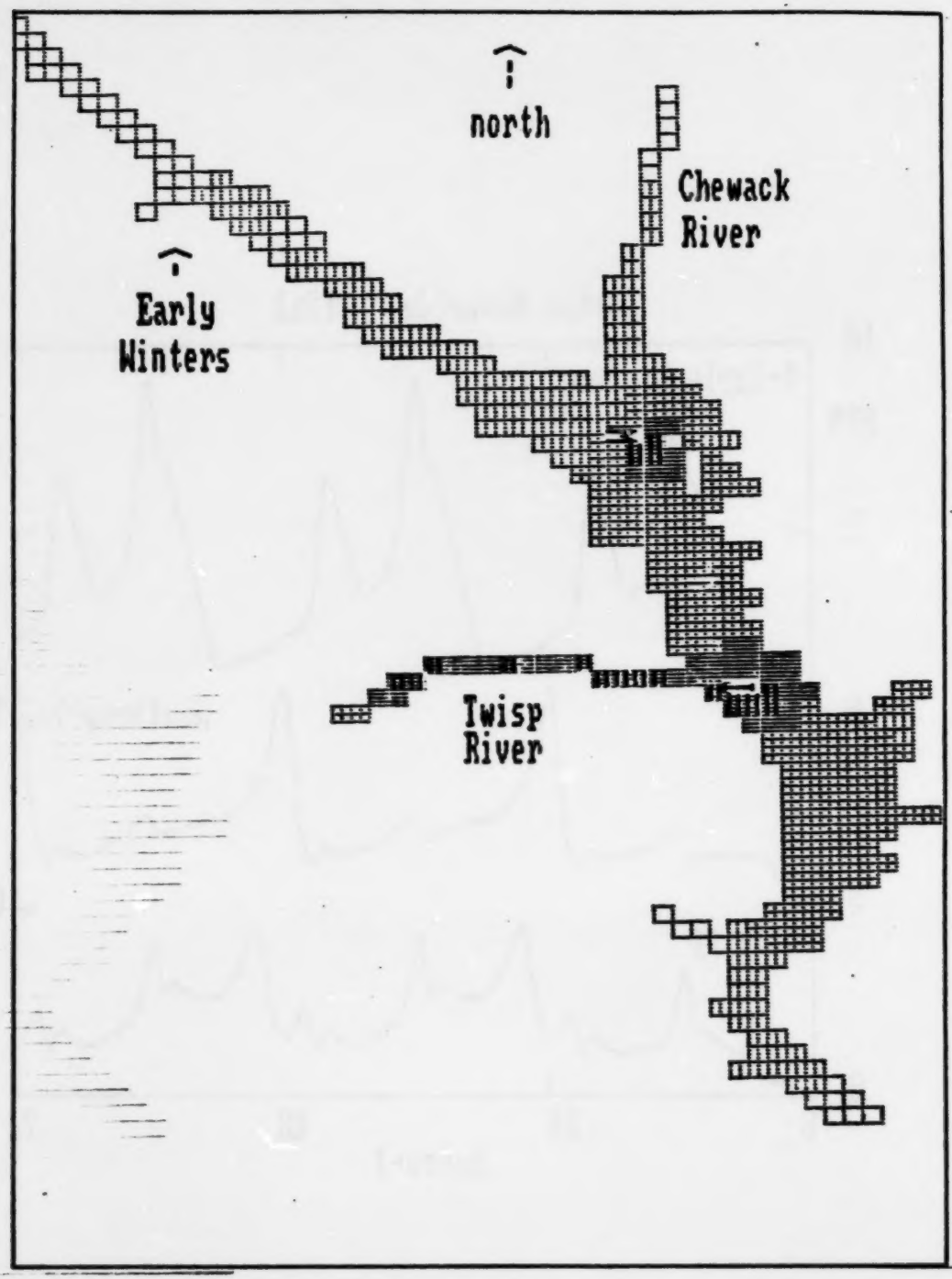


METHOW VALLEY AIR-QUALITY SIMULATION

3.88E+00 <	■	< 4.80E+00
2.96E+00 <	▦	< 3.88E+00
2.04E+00 <	⊞	< 2.96E+00
1.11E+00 <	⊟	< 2.04E+00
1.90E-01 <	□	< 1.11E+00 ppm

Figure V-2 (1a)

CO 24-hr. Avg. [1a]



METHOW VALLEY AIR-QUALITY SIMULATION

1.63E+00	■	2.00E+00
1.25E+00	■	1.63E+00
8.79E-01	⊞	1.25E+00
5.04E-01	⊟	8.79E-01
1.30E-01	□	5.04E-01 ppm

CO 24-hr. Avg. [1b]

Figure V-2 (1b)

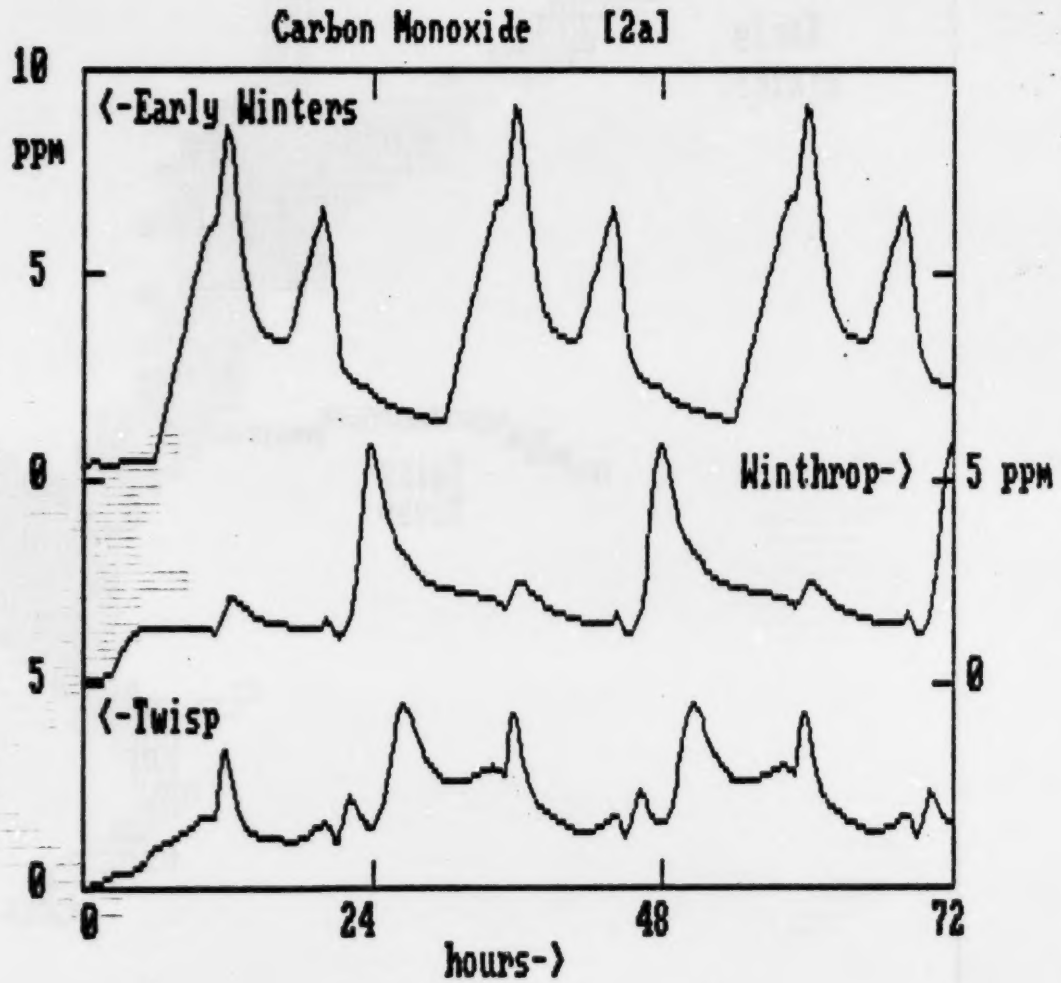

Carbon Monoxide [2a]
10
ppm
5
0
5
0
<-Early Winters
Winthrop->
5 ppm
0
<-Twisp
0
24
48
72
hours->

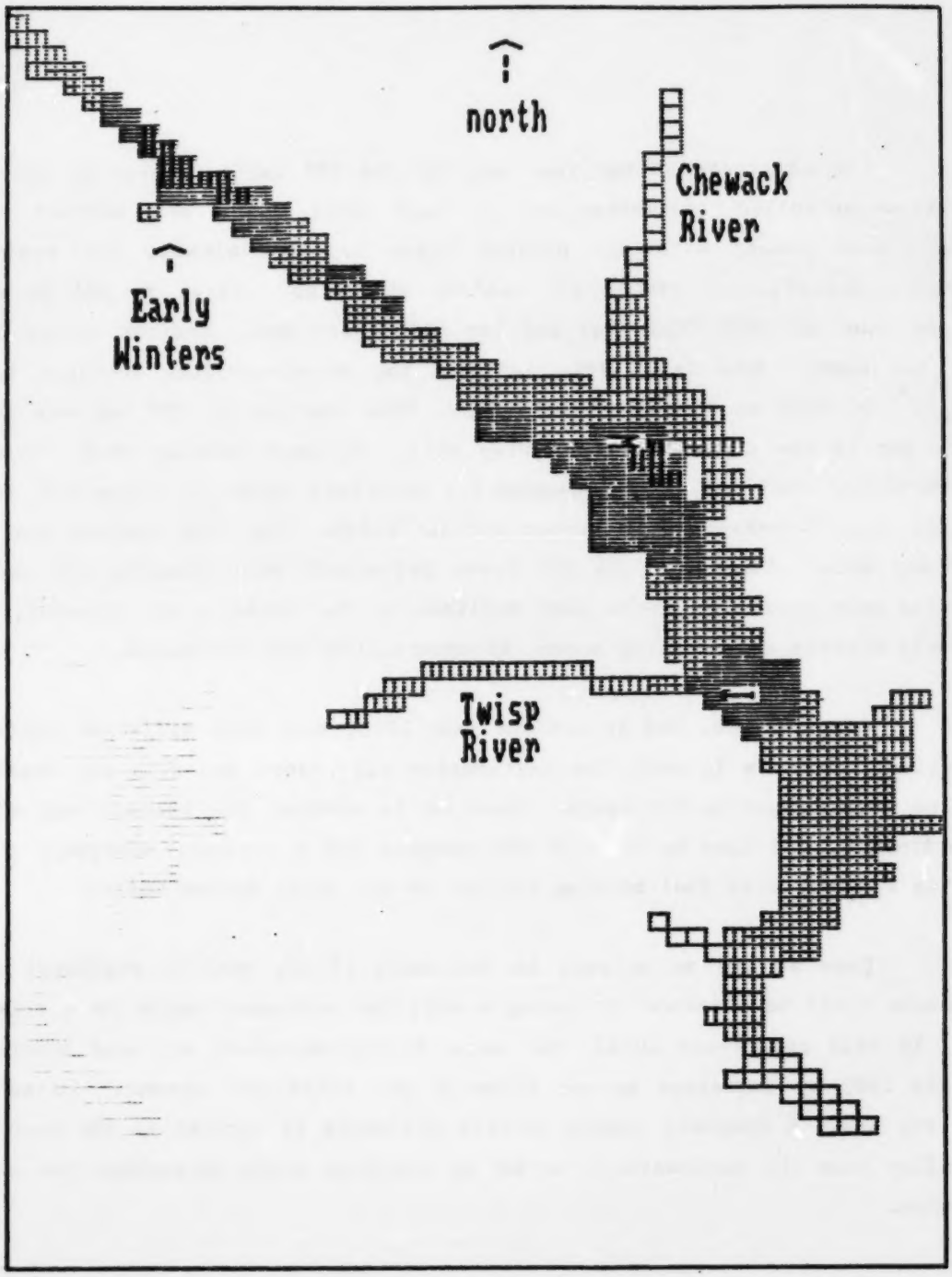
Figure V-3 (2a)

The remainder of the runs are for the TSP cases. Cases 2a and 2b project uncontrolled concentrations in year 2010, with and without the resort. Both cases, with the project (Case 2a) and without the project (Case 2b), dramatically exceed air quality standards. Cases 3a and 3b are baseline runs for 1978 (Case 3a) and for 1985 (Case 3b). Maximum values for these two cases, from Table V-1, indicate the maximum values decrease from 197 ug/m^3 in 1978 to 157 ug/m^3 for 1985. This decline in TSP maximum values is due to the closure of the Twisp mill. Although modeled peak concentration values declined, the concentration densities shown in Figure V-1 (3b) for 1985 have increased in the upper Methow Valley. The 1979 maximum was in the Twisp area. Subsequent to the Crown Zellerbach mill closure, the model indicates peak particle levels have declined in the Twisp area. However, in the Early Winters and Winthrop areas, concentrations have increased.

Cases 4a, 4b, and 4c are for year 2010, each with different control strategies. Case 4a is with the destination ski resort and with the Draft 5 Proposed County Interim Ordinance. Case 4b is without the project and with the ordinance, and Case 4c is with the project and a stricter ordinance prohibiting any new solid fuel burning devices in the upper Methow Valley.

Case 4c was an attempt to determine if air quality standards and increments could be attained by having a stricter ordinance apply to a select area. In this case (year 2010), the upper Valley emissions are kept constant with the 1985 by emissions by not allowing any additional stoves. In addition, the Draft 5 Proposed County Interim Ordinance is applied to the rest of the Valley from the northwestern border of Winthrop south throughout the modeled area.

The last five cases shown in Table V-1 and in Figure V-2 (4a-3a) to Figure V-2 (2b-3a) are the predicted increment usage for the TSP cases. The predicted impacts of the baseline year 1978 are subtracted from the predicted impacts in 2010 for each box, resulting in maps of predicted increment usage.

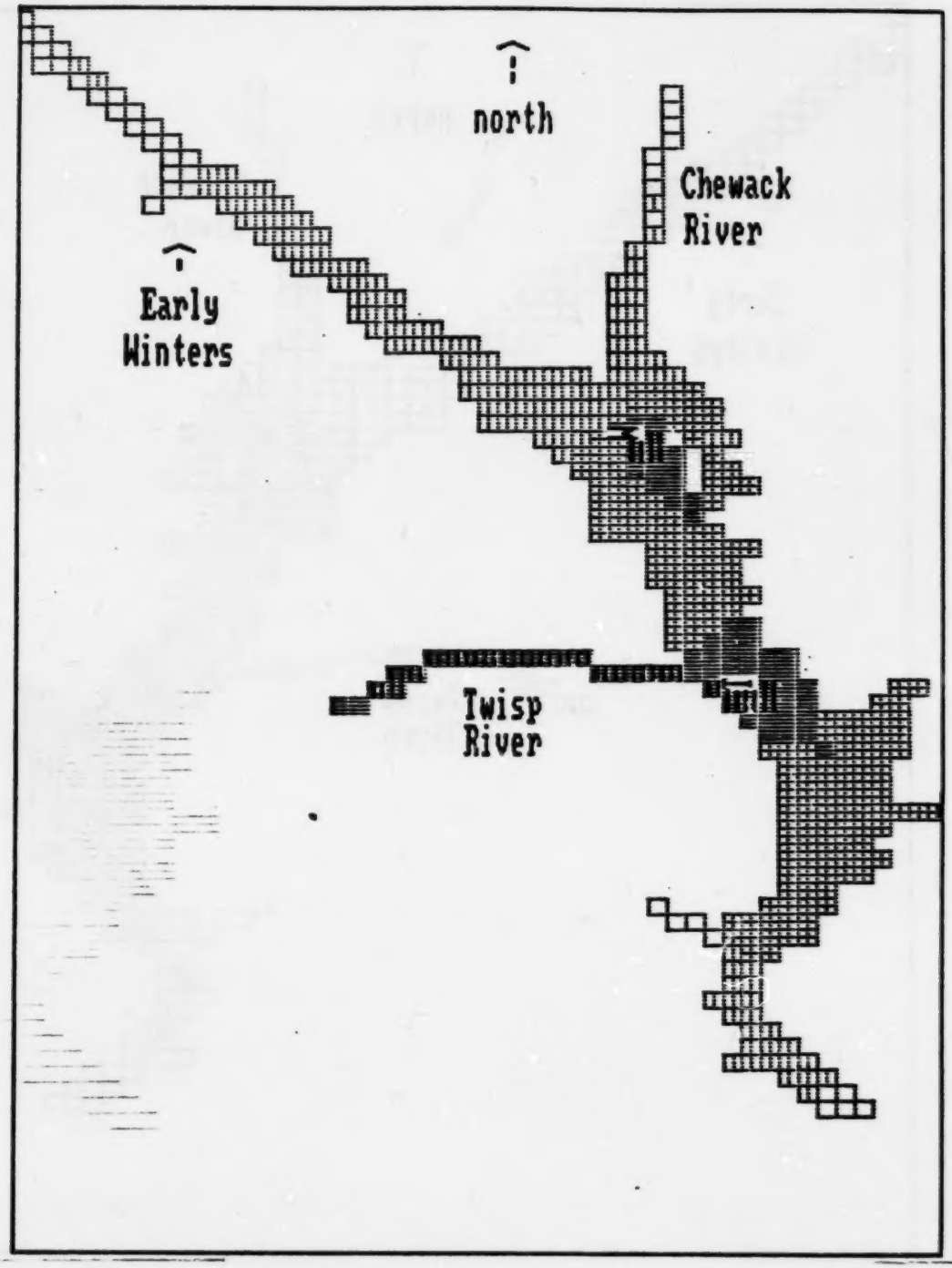


METHOW VALLEY AIR-QUALITY SIMULATION

4.35E+02	<	5.39E+02	
3.31E+02	<	4.35E+02	
2.27E+02	<	3.31E+02	
1.23E+02	<	2.27E+02	
1.96E+01	<	1.23E+02	MU gM/M^3

Figure V-4 (2a)

TSP 24-hr. Avg. [2a]

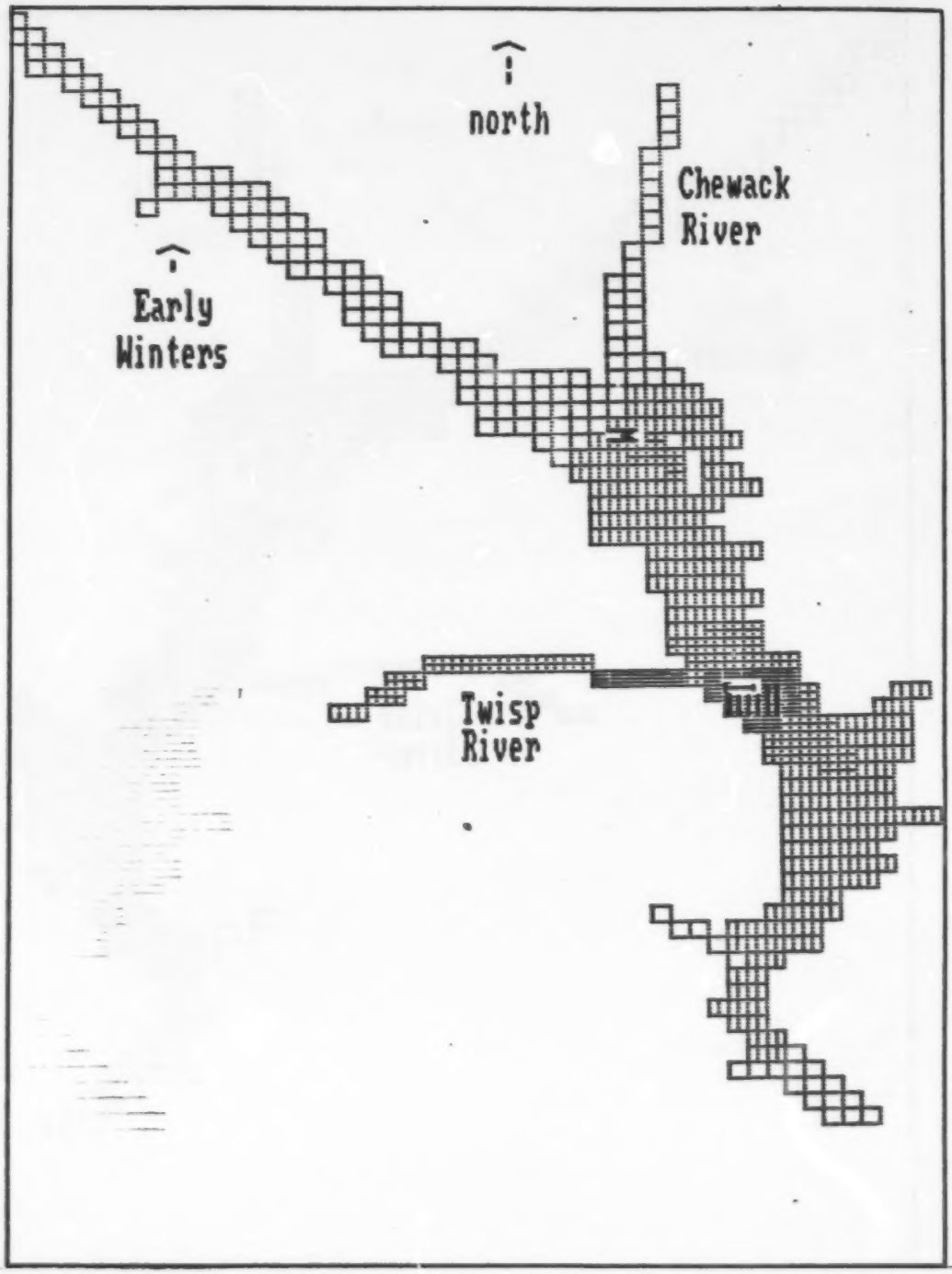


METHOW VALLEY AIR-QUALITY SIMULATION

2.68E+02	<	■	< 3.32E+02
2.05E+02	<	■	< 2.68E+02
1.42E+02	<	⊞	< 2.05E+02
7.83E+01	<	⊟	< 1.42E+02
1.49E+01	<	□	< 7.83E+01 mu gm/m^3

Figure V-4 (2b)

TSP 24-hr. Avg. [2b]

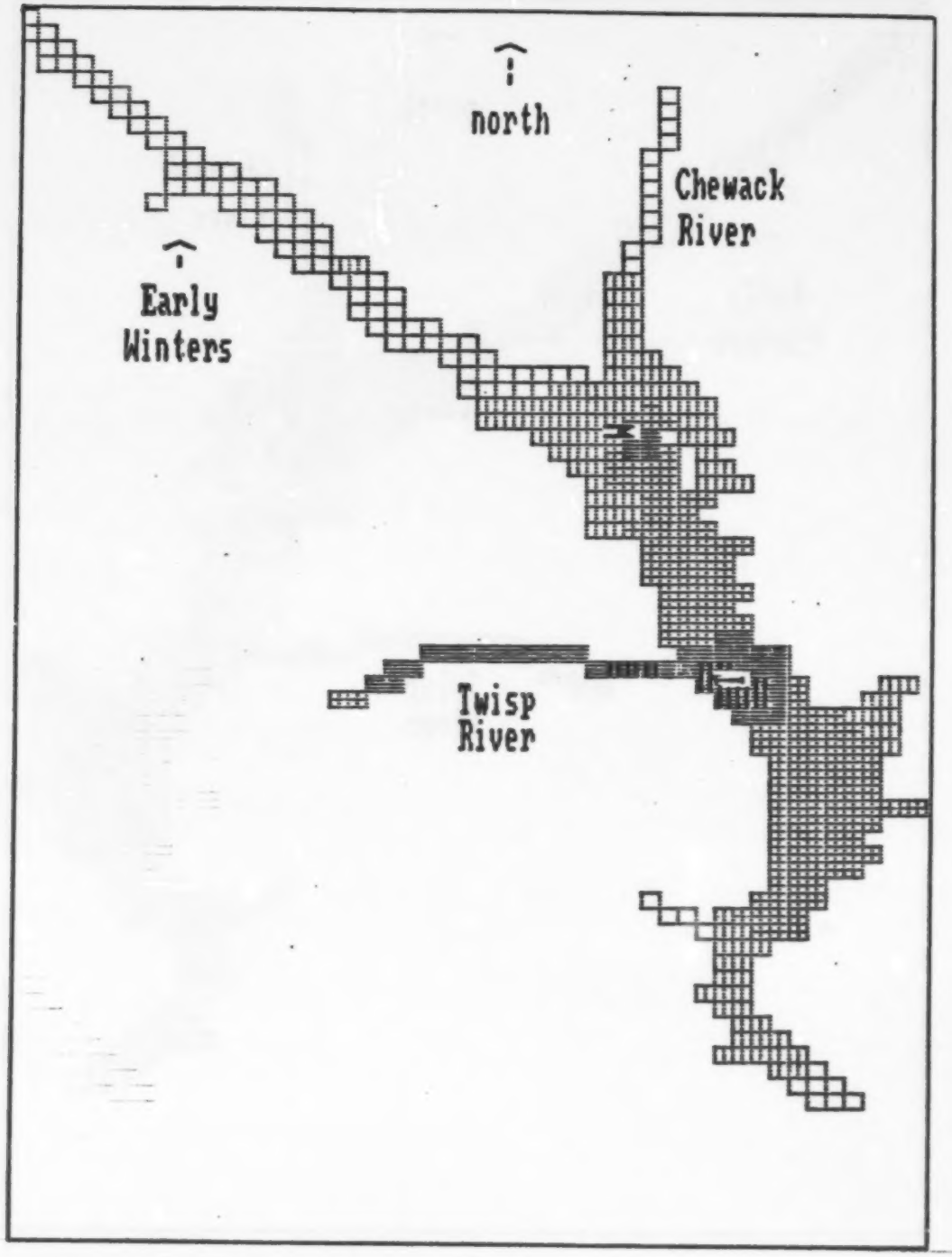


METHOW VALLEY AIR-QUALITY SIMULATION

1.58E+02 < ■ < 1.97E+02
1.20E+02 < ■ < 1.58E+02
8.10E+01 < ⊞ < 1.20E+02
4.24E+01 < ⊟ < 8.10E+01
3.88E+00 < □ < 4.24E+01 mu gm/m^3

Figure V-4 (3a)

TSP 24-hr. Avg. [3a-1979]

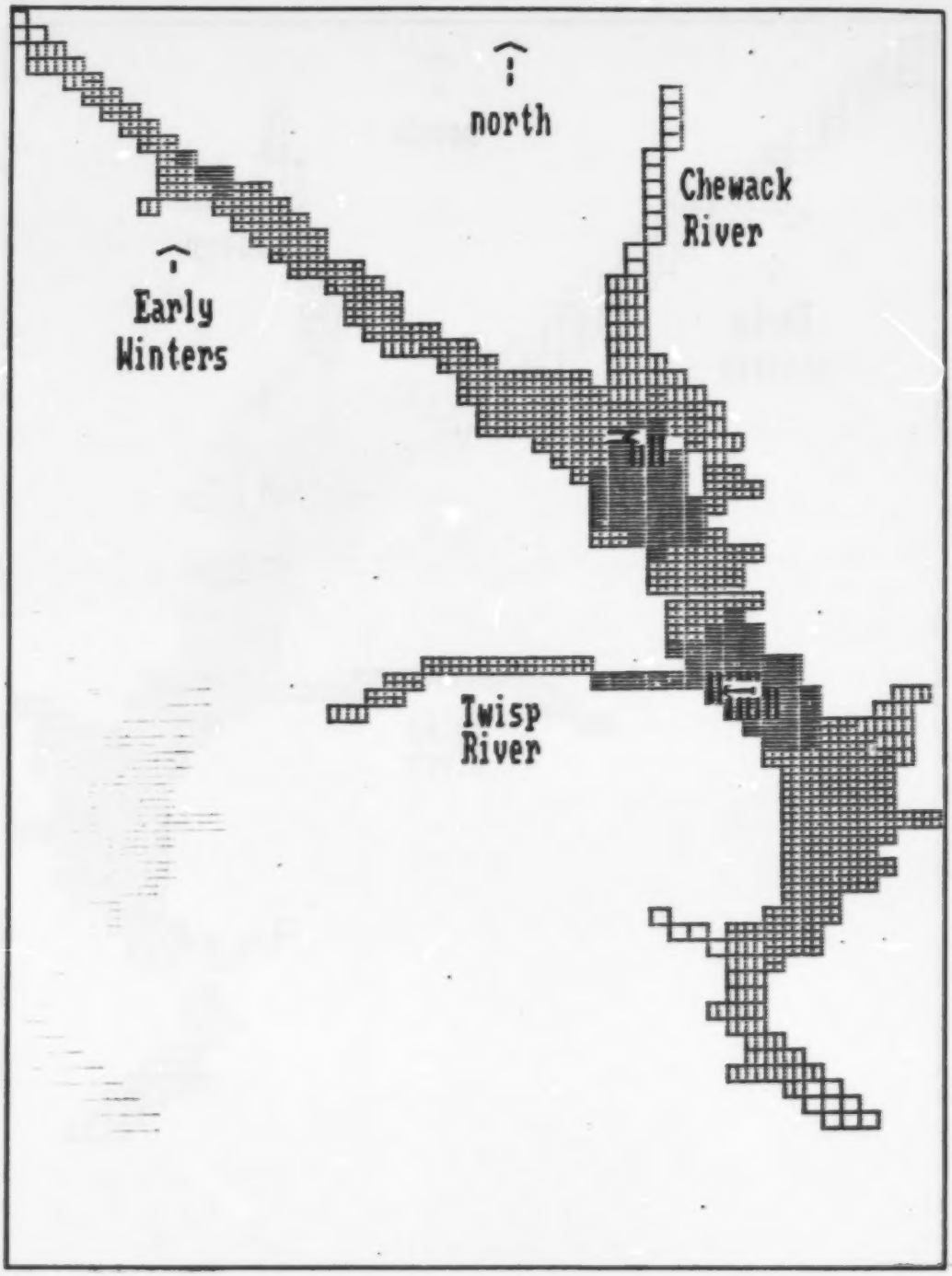


METHOW VALLEY AIR-QUALITY SIMULATION

1.26E+02 < ■ < 1.57E+02
9.61E+01 < ■ < 1.26E+02
6.58E+01 < ⊞ < 9.61E+01
3.55E+01 < ⊟ < 6.58E+01
5.25E+00 < □ < 3.55E+01 mu gm/m^3

Figure V-4 (3b)

TSP 24-hr. Avg. [3b-1985]

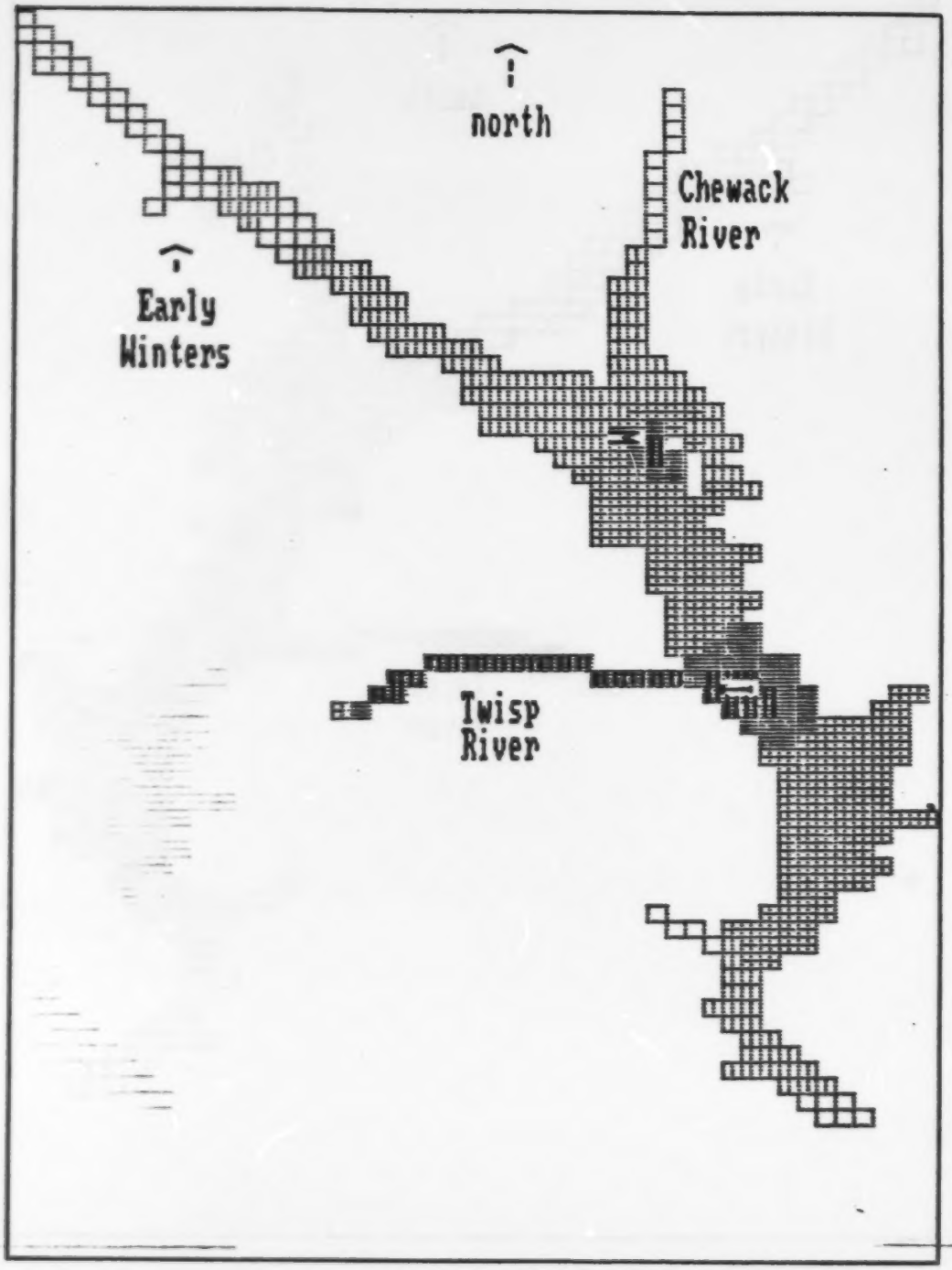


METHOW VALLEY AIR-QUALITY SIMULATION

1.82E+02	<	■	< 2.25E+02
1.39E+02	<	■	< 1.82E+02
9.57E+01	<	⊞	< 1.39E+02
5.26E+01	<	⊟	< 9.57E+01
9.55E+00	<	□	< 5.26E+01 mu gm/m^3

Figure V-4 (4a)

TSP 24-hr. Avg. [4a]

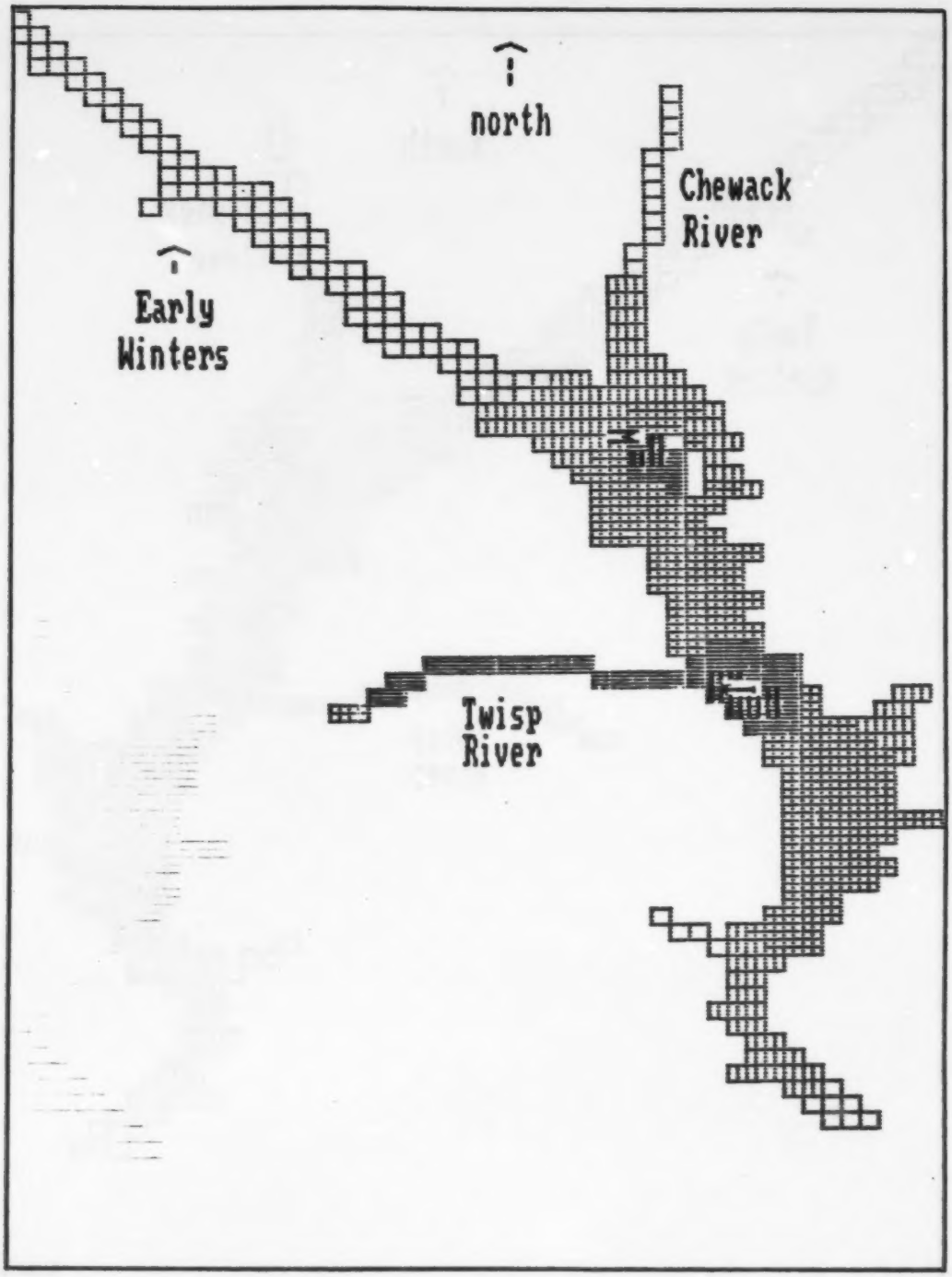


METHOW VALLEY AIR-QUALITY SIMULATION

1.57E+02 <	■	< 1.95E+02
1.20E+02 <	■	< 1.57E+02
8.25E+01 <	⊞	< 1.20E+02
4.51E+01 <	⊟	< 8.25E+01
7.74E+00 <	□	< 4.51E+01 mu gm/m^3

TSP 24-hr. Avg. [4b]

Figure V-4 (4b)

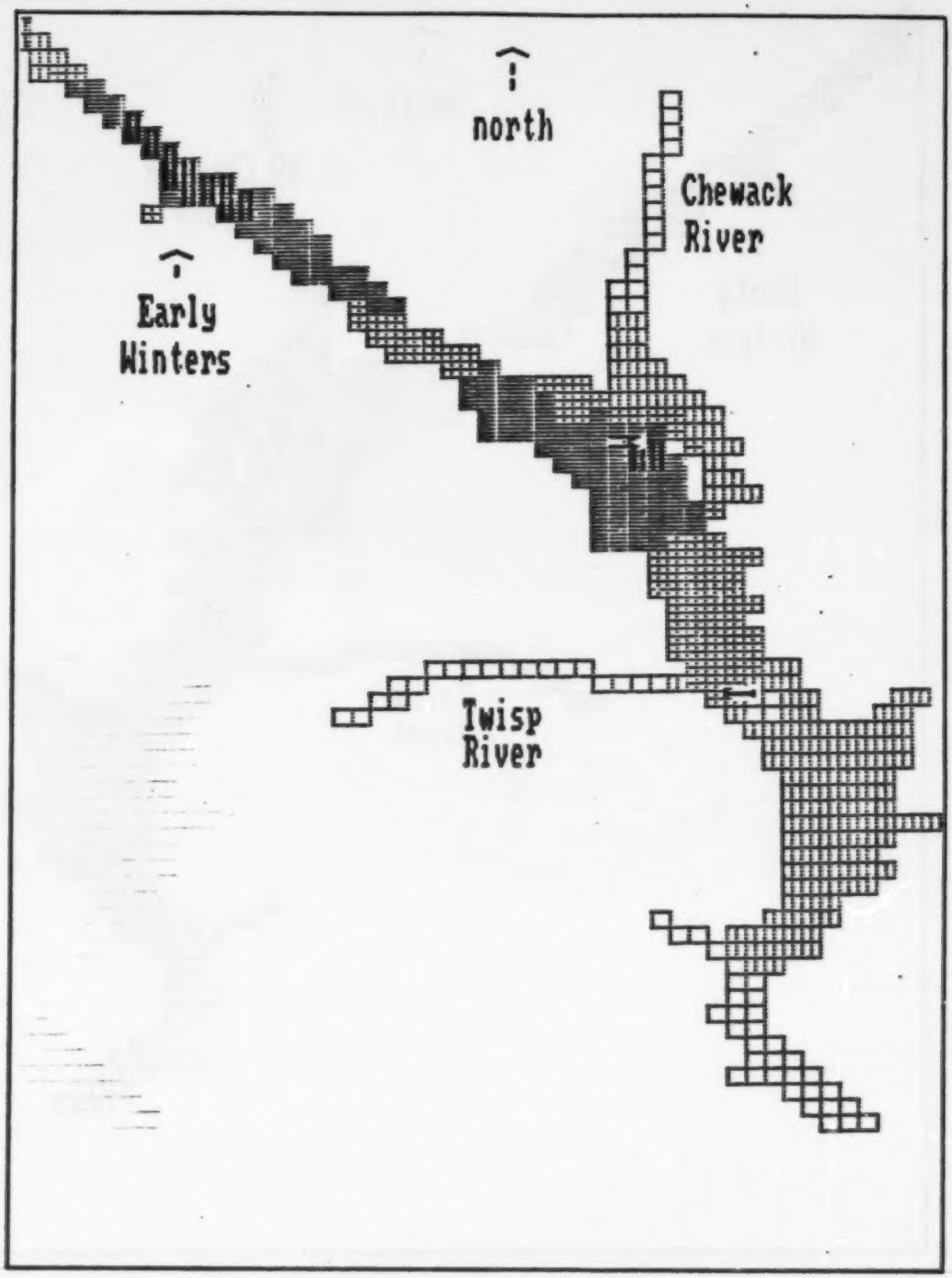


METHOW VALLEY AIR-QUALITY SIMULATION

1.46E+02	<	■	< 1.81E+02
1.11E+02	<	▦	< 1.46E+02
7.57E+01	<	⊞	< 1.11E+02
4.05E+01	<	⊟	< 7.57E+01
5.25E+00	<	□	< 4.05E+01 mu gm/m^3

TSP 24-hr. Avg. [4c]

Figure V-4 (4c)

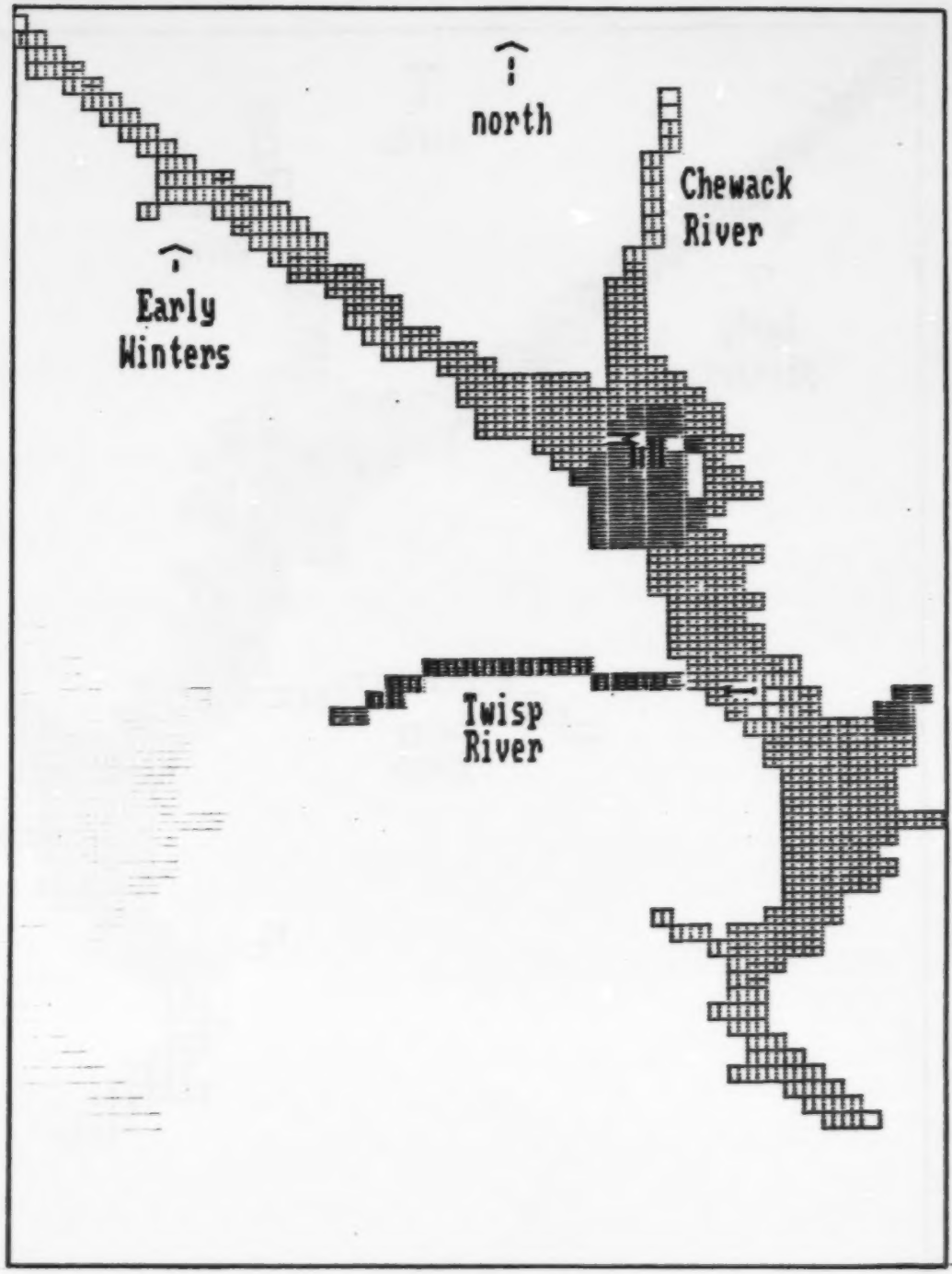


METHOW VALLEY AIR-QUALITY SIMULATION

1.01E+02	<	■	< 1.25E+02
7.65E+01	<	■	< 1.01E+02
5.22E+01	<	⊞	< 7.65E+01
2.79E+01	<	⊟	< 5.22E+01
3.55E+00	<	□	< 2.79E+01 mu gm/m^3

Figure V-5 (4a-3a)

TSP 24-hr. Avg [4a-3a]

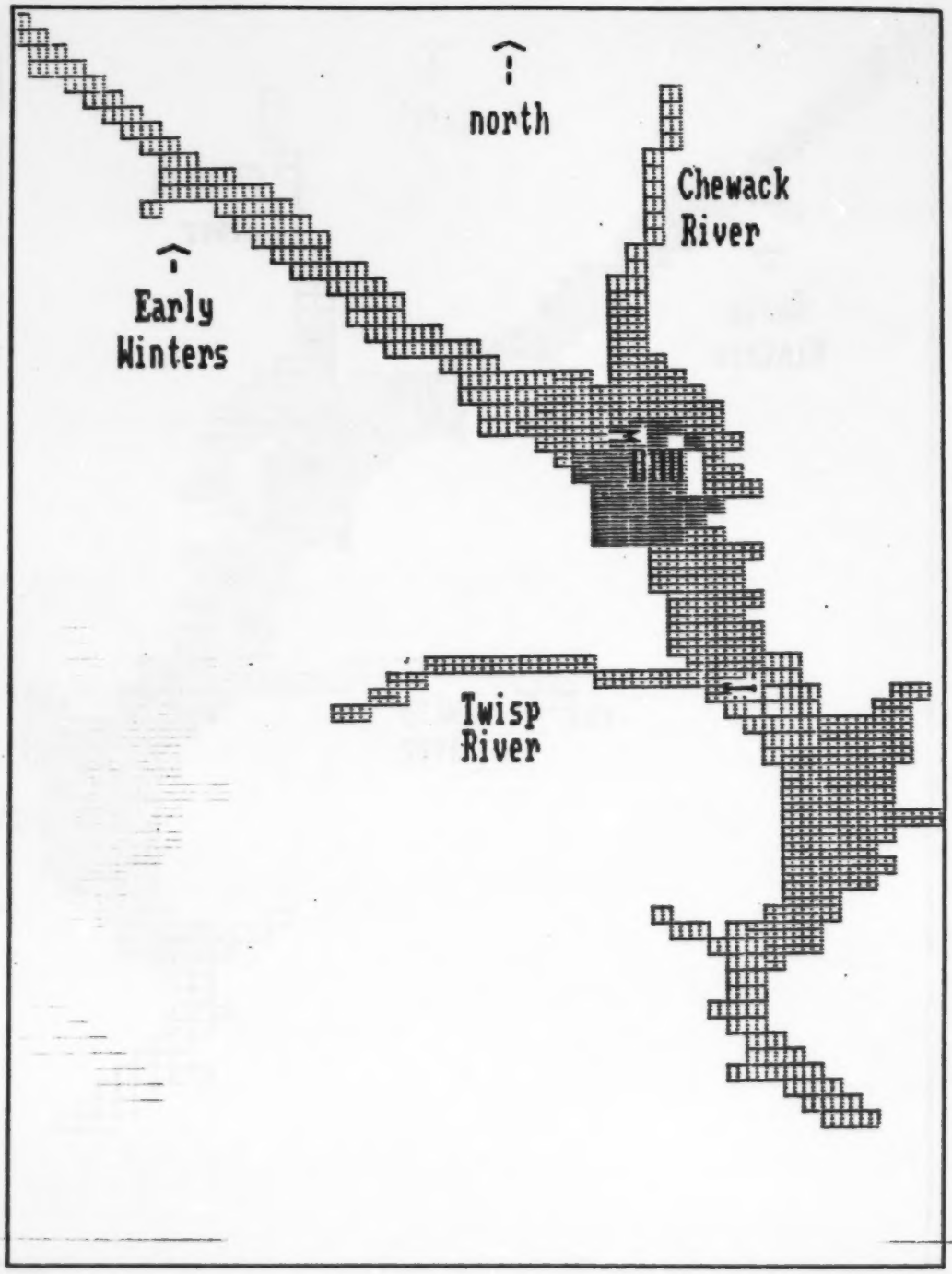


METHOW VALLEY AIR-QUALITY SIMULATION

5.01E+01	<	■	< 6.44E+01
3.58E+01	<	■	< 5.01E+01
2.14E+01	<	⊞	< 3.58E+01
7.12E+00	<	⊟	< 2.14E+01
-7.20E+00	<	□	< 7.12E+00 mu gm/m^3

Figure V-5 (4b-3a)

TSP 24-hr. Avg. [4b-3a]

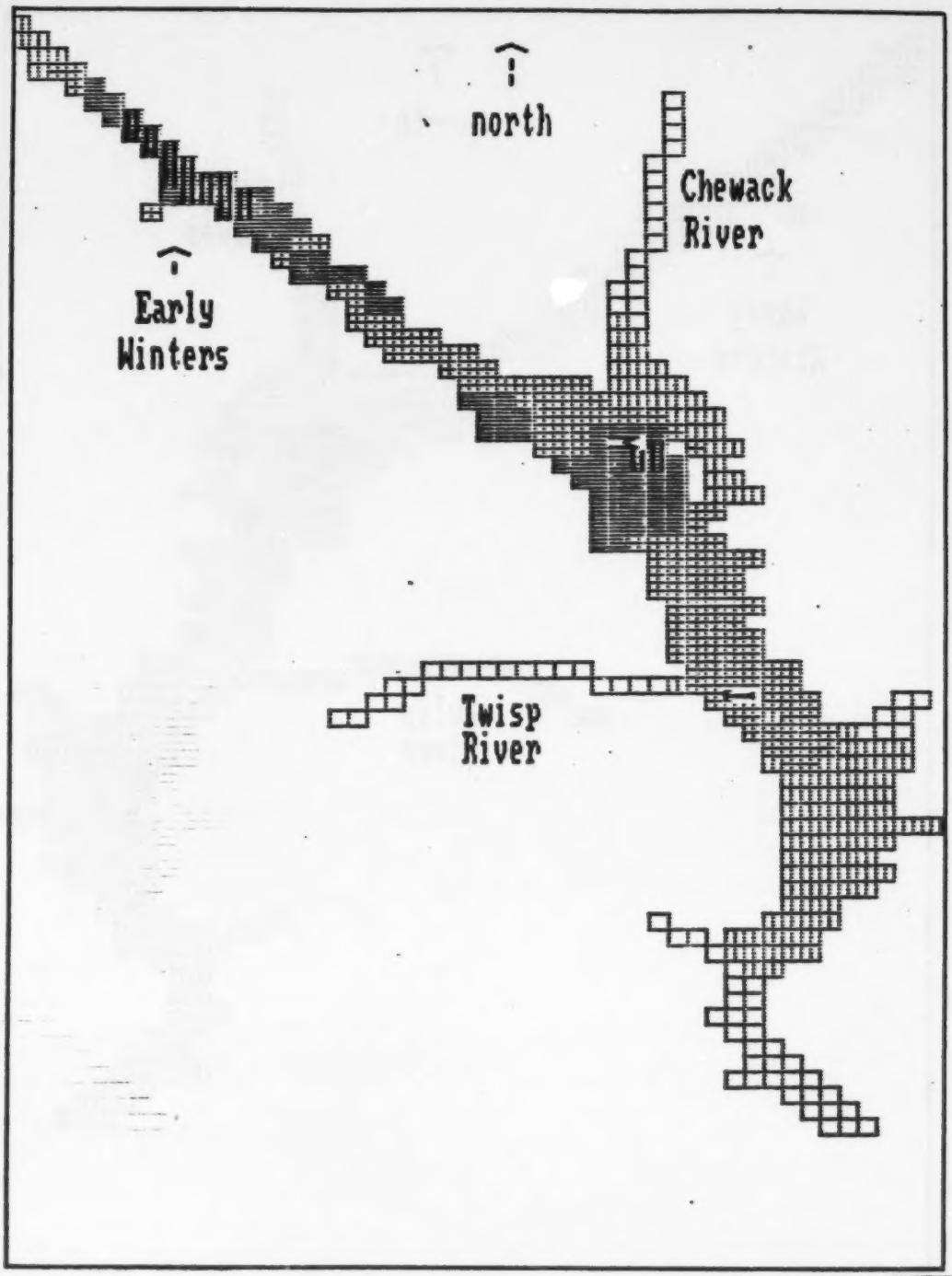


METHOW VALLEY AIR-QUALITY SIMULATION

4.59E+01 <	■	< 6.26E+01
2.91E+01 <	▦	< 4.59E+01
1.24E+01 <	⊞	< 2.91E+01
-4.36E+00 <	⊟	< 1.24E+01
-2.11E+01 <	□	< -4.36E+00 mu gm/m^3

Figure V-5 (4c-3a)

TSP 24-hr. Avg. [4c-3a]

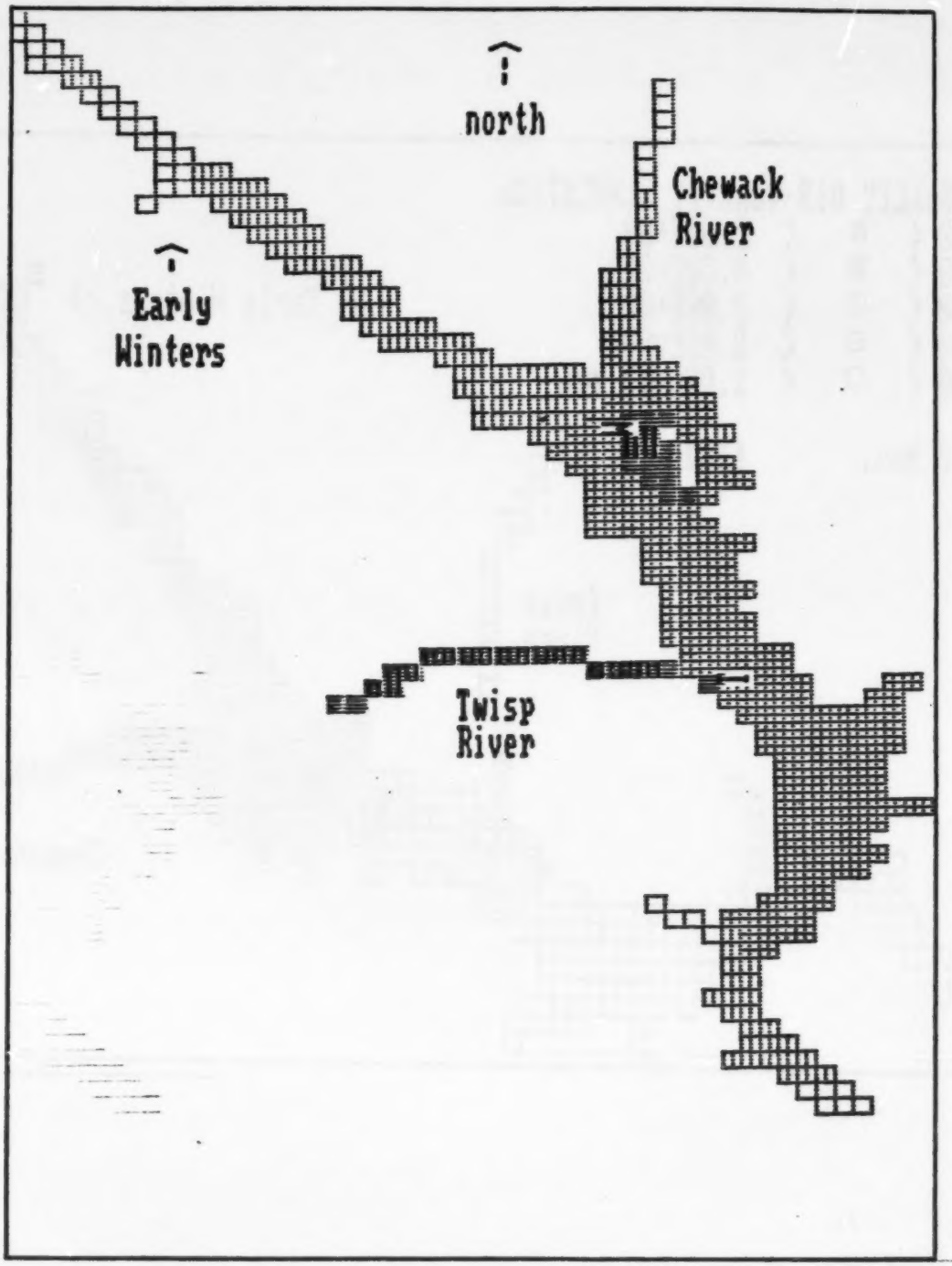


METHOW VALLEY AIR-QUALITY SIMULATION

3.94E+02	<	■	< 4.89E+02
2.99E+02	<	▦	< 3.94E+02
2.04E+02	<	⊞	< 2.99E+02
1.09E+02	<	⊟	< 2.04E+02
1.36E+01	<	□	< 1.09E+02 mu gm/m^3

Figure V-5 (2a-3a)

TSP 24-hr. Avg. [2a-3a]



METHOW VALLEY AIR-QUALITY SIMULATION

1.77E+02	<	■	< 2.19E+02
1.36E+02	<	■	< 1.77E+02
9.42E+01	<	⊞	< 1.36E+02
5.26E+01	<	⊟	< 9.42E+01
1.10E+01	<	□	< 5.26E+01 mu gm/m^3

Figure V-5 (2b-3a)

TSP 24-hr. Avg. [2b-3a]

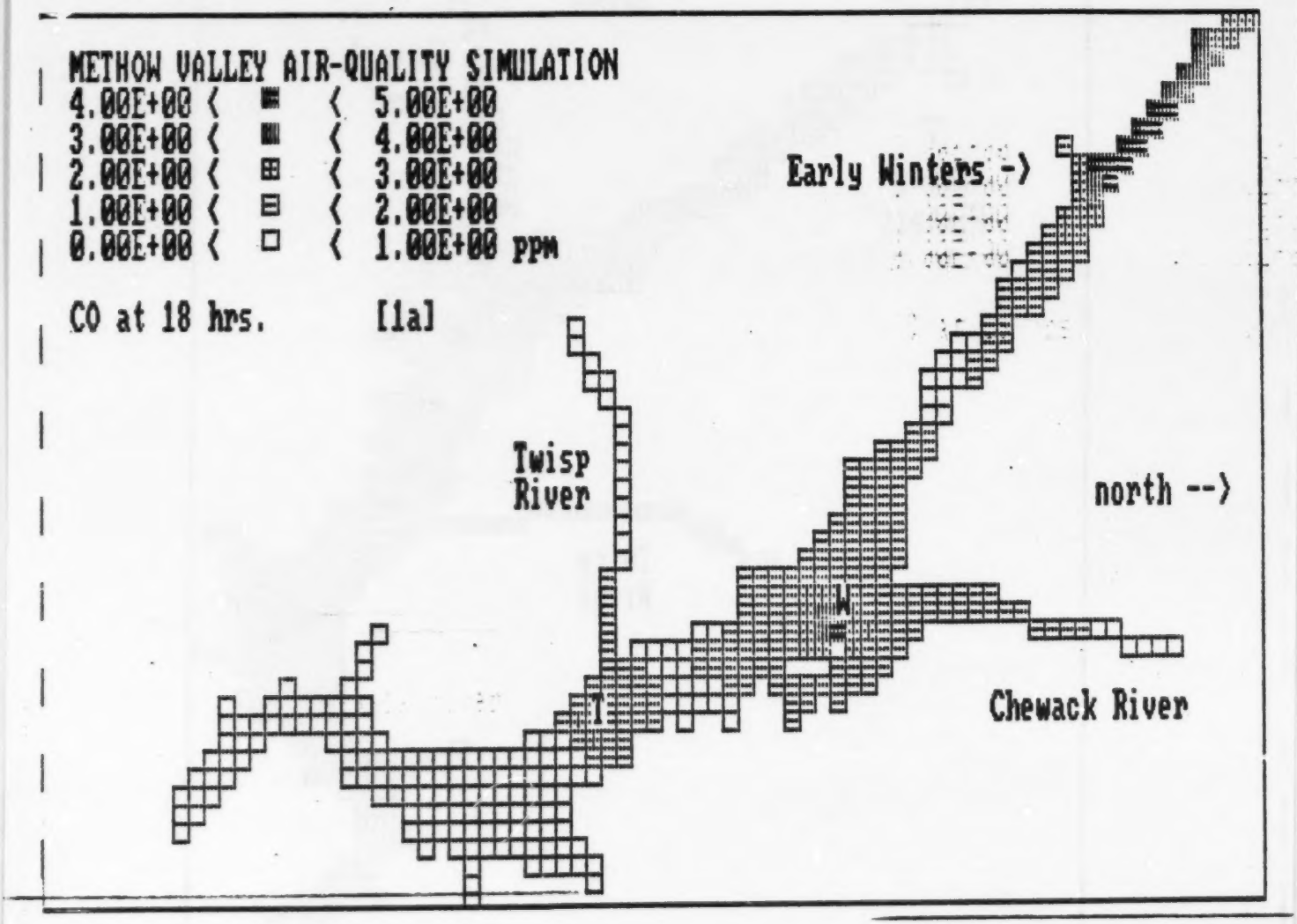

METHOW VALLEY AIR-QUALITY SIMULATION
4.00E+00 < ■ < 5.00E+00
3.00E+00 < ■ < 4.00E+00
2.00E+00 < ⊞ < 3.00E+00
1.00E+00 < ⊟ < 2.00E+00
0.00E+00 < □ < 1.00E+00 ppm
CO at 18 hrs. [1a]
Early Winters ->
Twisp River
north -->
Chewack River

Figure 9.18

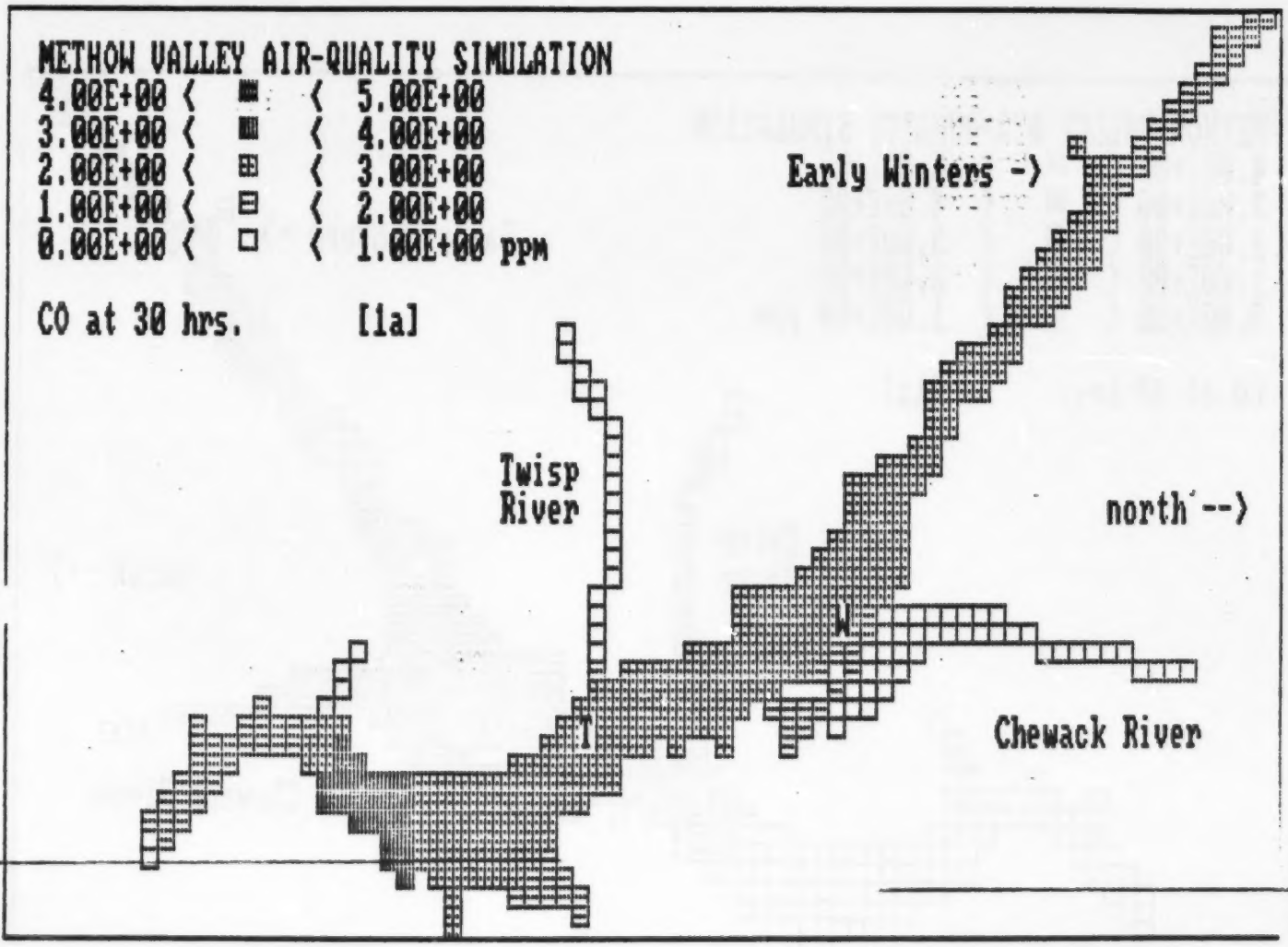

METHOW VALLEY AIR-QUALITY SIMULATION
4.00E+00 < ■ < 5.00E+00
3.00E+00 < ■ < 4.00E+00
2.00E+00 < ⊞ < 3.00E+00
1.00E+00 < ⊟ < 2.00E+00
0.00E+00 < □ < 1.00E+00 ppm
CO at 30 hrs. [1a]
Early Winters ->
Twisp River
north -->
W
T
Chewack River

Figure 9.30

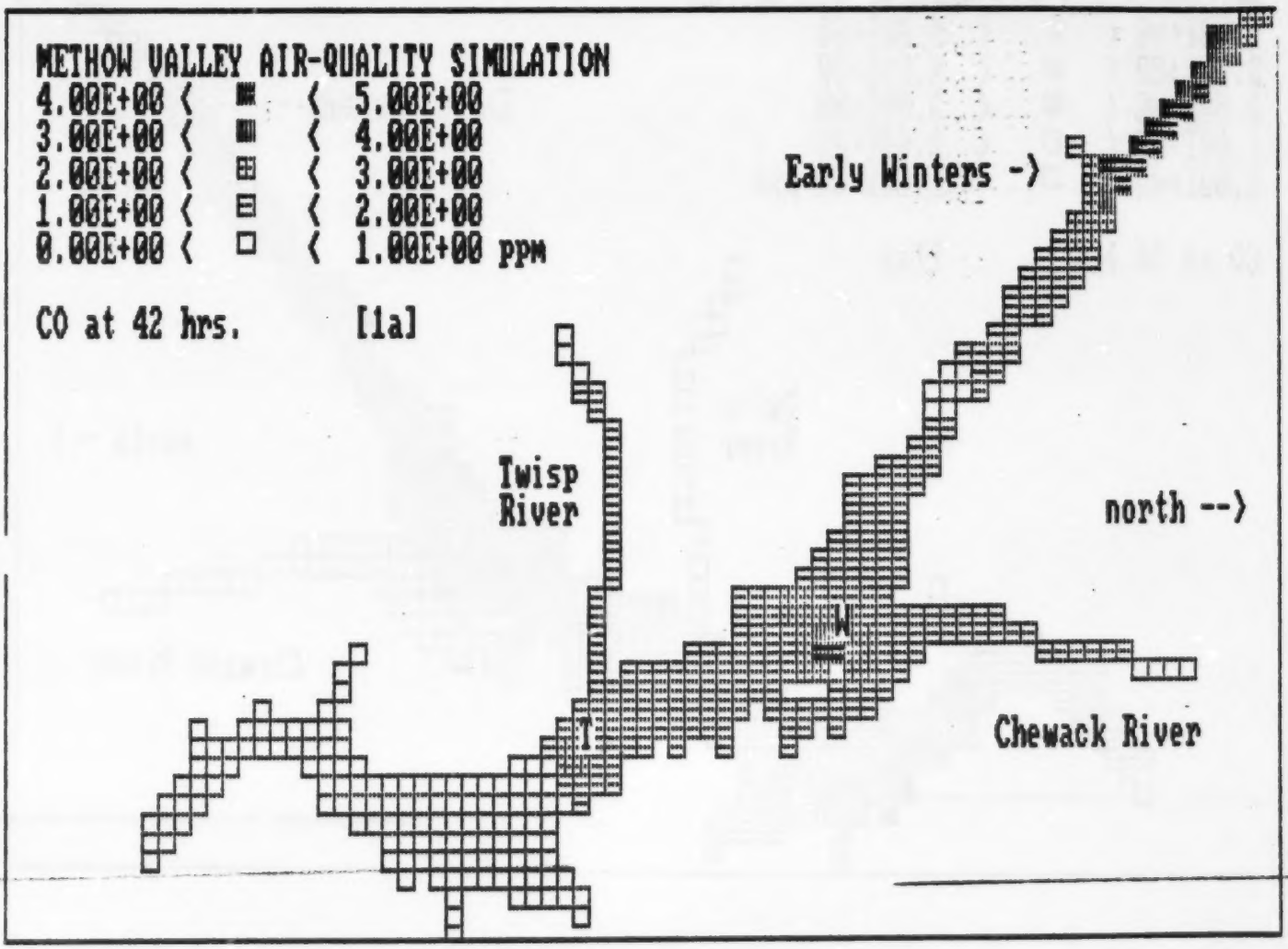

METHOW VALLEY AIR-QUALITY SIMULATION
4.00E+00 < ▪ < 5.00E+00
3.00E+00 < ▪ < 4.00E+00
2.00E+00 < ⊞ < 3.00E+00
1.00E+00 < ⊟ < 2.00E+00
0.00E+00 < □ < 1.00E+00 ppm
CO at 42 hrs. [1a]
Early Winters ->
Twisp River
north -->
W
T
Chewack River

Figure 9.42

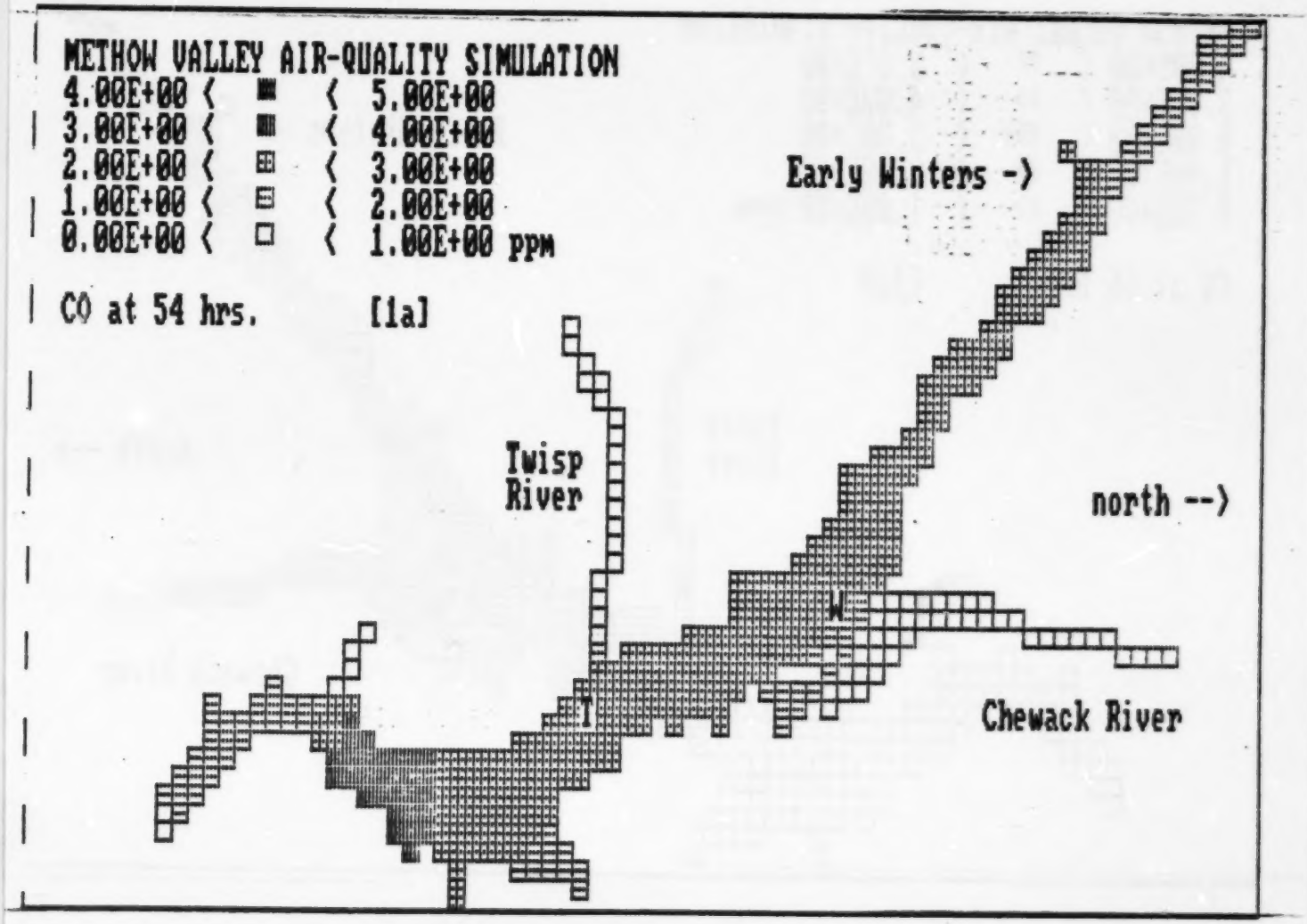

METHOW VALLEY AIR-QUALITY SIMULATION
4.00E+00 < < 5.00E+00
3.00E+00 < < 4.00E+00
2.00E+00 < < 3.00E+00
1.00E+00 < < 2.00E+00
0.00E+00 < < 1.00E+00 ppm
CO at 54 hrs. [1a]
Early Winters ->
Twisp River
north -->
W
T
Chewack River

Figure 9.5b

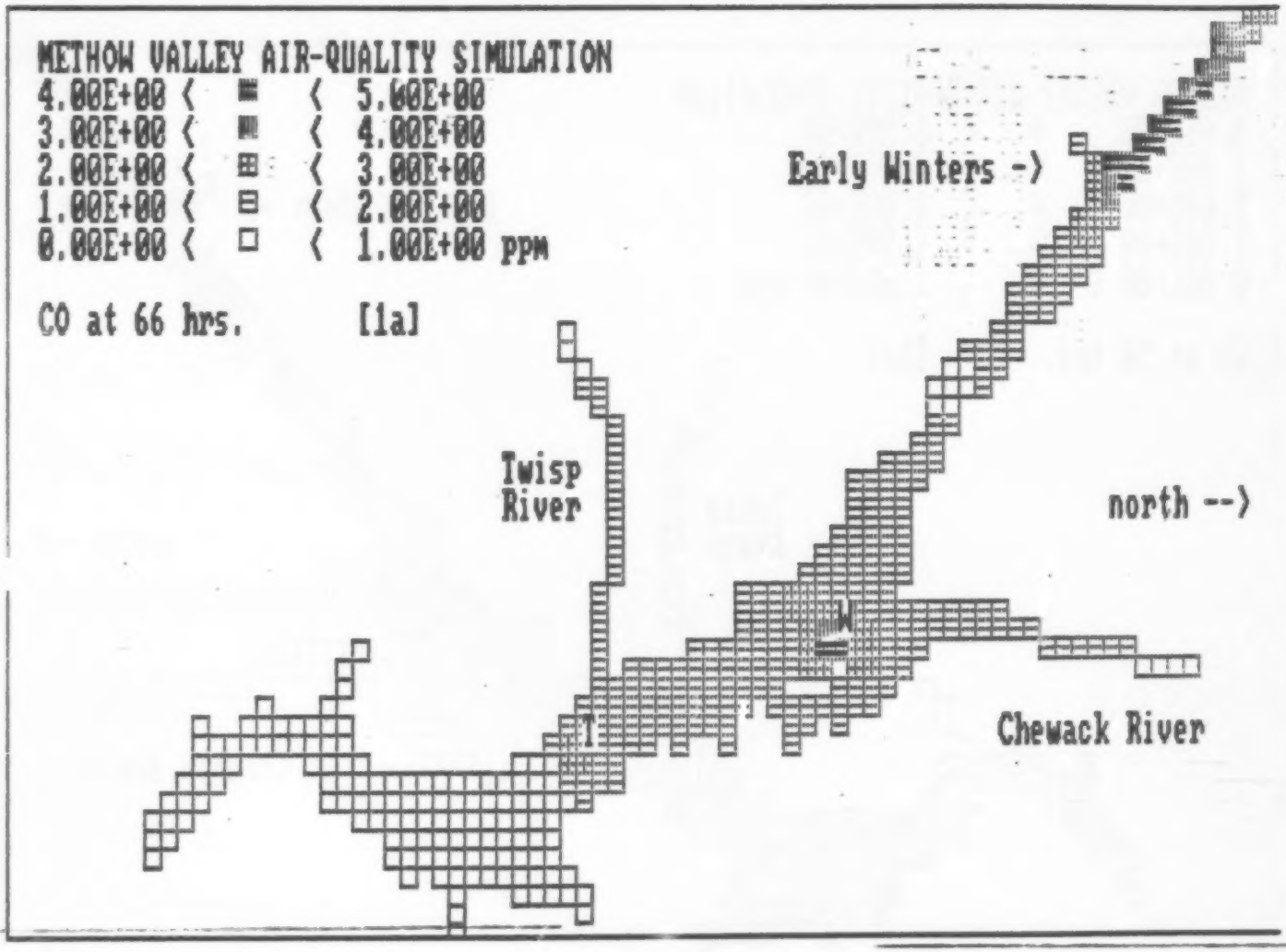

METHOW VALLEY AIR-QUALITY SIMULATION
4.00E+00 < ▪ < 5.60E+00
3.00E+00 < ▪ < 4.00E+00
2.00E+00 < ▪ < 3.00E+00
1.00E+00 < ▪ < 2.00E+00
0.00E+00 < □ < 1.00E+00 ppm
CO at 66 hrs. [1a]
Early Winters ->
Twisp River
north -->
W
T
Chewack River

Figure 9.66

Appendix III

Correspondence re Conservation of Mass with D.G. Fox

Diffusivities from Gifford-Pasquil-Turner Stabilities							
σ_y = 0.5 mile u = 1 mph							
Class	X_o	α_y	K_y	α_z	K_z	$R_{s,y}$	R_z
	km		$m^2 s^{-1}$		$m^2 s^{-1}$	hrs^{-1}	hrs^{-1}
A	4.5	0.91	58.4	1.96	17.5	6.31	0.325
B	6.2	0.91	42.4	1.10	5.5	1.97	0.236
C	9.5	0.91	27.6	0.92	2.42	0.87	0.154
D	15.5	0.91	17.0	0.52	0.38	0.139	0.094
E	21.0	0.91	12.5	0.48	0.126	0.045	0.070
F	43.0	0.91	6.1	0.44	0.018	0.006	0.034

The preceding table presents conversions from G-P-T stability classes, for $\sigma_{s,y} = \delta x = \delta y = 0.5$ miles = 804 meters, $\delta z = 100$ meters, and $u = 1$ mph = 0.44 ms^{-1}. Shown also on this table are values for $R_{s,y}$ and R_z in units of reciprocal hours. These latter two numbers are the coefficients to be used by the model for vertical ventilation and horizontal diffusion, respectively. At various times in the campaign of simulations values of R_z were explored between .04 and 0.25 hrs^{-1}, and $R_{s,y}$ between 0 and 3 hrs^{-1}. The plots and tables of Appendix I were computed with $R_z = 0.10$ hrs^{-1} between 10 AM and 5 PM, and 0.04 hrs^{-1} at other times. These values correspond to G-P-T stability classes D and F, respectively. Similarly, the $R_{s,y}$ were taken as proportional to the wind speeds plus 1 mph, and ranged between 1 and 3 hrs^{-1}, corresponding to stability classes C and B.

The dispersion parameters chosen for the Methow valley simulation were necessarily somewhat arbitrary. It is not clear that G-P-T stabilities are very appropriate in complex terrain, with a snow covered valley floor, and with short days and large solar zenith angles. (Bowling, 1985; Hunt, 1985; Weil, 1985; Wyngaard, 1985) Remember please, that the σ_y derive ultimately from meandering wind directions: these clearly are greatly enhanced by the valley contours: hence the choice of transverse diffusivities corresponding to relatively unstable G-P-T classes. I remark, however, that the resulting simulations are fairly insensitive to this parameter, owing to confinement by the valley walls. The choice of R_z, on

the other hand, is quite critical. Modifications necessary for dispersion models at high latitudes are discussed by Bowling (1985), who recommends a modification of stability classification procedures that is based on lapse rates and average solar angles. The R_i values chosen for this study are by Bowling's classification more nearly C-D.

I remark that for all one-layer models with horizontal flows, only, numerical diffusion in the vertical coordinate is identically zero. With the present box sizes, time steps, and winds the numerical diffusion in the horizontal coordinates is less than 0.4 times the 'real' diffusion, in the worst case.

C. The Model's Output.

A summary of computed 24-hr maximum TSP and CO, for 1978 and 1985 baselines, and for various scenarios for source growth and emission controls is presented in Appendix I, Table V-1. A discussion of results precedes this table on page V-4. Read this, please. In general terms, the model predicts CO levels marginally below maximum standards, and TSP significantly above them. For the 1985 baseline case the predicted maximum TSP at Winthrop was about 30% higher than that observed. Models of this family are often advertised as excellent if they "agree within a factor of two for 50% of the cases" ... a very modest achievement, as it seems to me. There is a class of errors that would be expected to be minimized when comparing changes from one scenario to another, in percentage terms. Guessing, only, I would hope that these relative estimates might be accurate to perhaps 25-50% (of the percentages). One strength of this class of models lies in their mapping both temporal and spatial patterns, and consequently one of their better uses may be to assist the placement of detectors ... given time and money. The model suggests that impacts will be concentrated near Winthrop, and in the upper Methow and Twisp rivers.

D. Some Concluding Remarks

Appendix III contains some correspondence concerning some limitations of two dimensional models with constant winds in valleys of varying cross section.

It is my understanding that some controversy has followed the management plan for maintaining air quality in the Methow valley. Among the model's assumptions that have been challenged are estimates of woodsmoke emission factors for various fuels and stoves. The long string of explicit approximations of the transport equations that I have emphasized in the preceding section II of this report, together with those assumptions and guesses associated with the present implementation of the current box model to this river-valley system should make clear that air-quality modeling remains an approximate art.

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June 30, 1985

METHOW VALLEY AIR QUALITY STUDY AND MANAGEMENT PLAN

by

R. W. BECK AND ASSOCIATES

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Planning Director
Stephen Burgor

Okanogan County Planning Department
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Okanogan, Washington 98440

United States Department of Agriculture
Forest Service
Rocky Mountain Forest and Range Experiment Station
240 West Prospect Street
Fort Collins, CO 80526

RECEIVED
MAY 20 1985
R. W. BECK and ASSOC.
Seattle, Wash.

Reply to

Date May 14, 1985

Naydene Maykut
R. W. Beck and Associates
Tower Building
7th Avenue at Olive Way
Seattle, WA 98101

Dear Ms. Maykut:

I find one major difficulty with the model proposed by Harrison and it may be simply a matter of semantics. I am a bit surprised with the assumptions related to the coupling between boxes. Obviously the conservation of mass, momentum, and energy should be observed. Mention is made that the numerical code "conserves mass" but there is not sufficient information to determine whether this is true for the model as a whole. For example, it is stated that concentration flux is linearly proportional to concentration in each box. Does this mean that concentration cannot accumulate in a cell as a result of convergence of the transport wind? I assume the statement applies to a gradient transport-eddy diffusivity term which is independent of the advection of concentration. If so the model is okay; if not then I would really question its utility.

Parameter values seem appropriate.

Sincerely,

DOUGLAS G. FOX
Chief Meteorologist

WYNDsoft
6333 77th Avenue SE
Mercer Island
WA 98040
July 9, 1985

Dr. Douglas G. Fox
Rocky Mountain Forest and Range Experiment Station
240 West Prospect Street
Fort Collins, CO 80526

Dear Dr. Fox:

On May 14 of this year, I believe in response to a letter requesting your review of a dispersion model proposed for estimating impacts of various development senarios upon the Methow Valley, in Okanogan County, Washington, you wrote a letter to Ms. Naydene Maykut of R.W. Beck Associates. You then expressed some concerns about it; in particular, you were concerned whether the model conserves mass as a whole, and whether local advective convergence is permitted, as contrasted with convergence from gradient transport-eddy diffusivity.

Naydene passed a copy of your letter to me for my response, which I delayed in the rush to make deadlines for delivering the model's output to her ... not the best of sequences, where preferably the model's assumptions and structure should be thrashed out long ahead. In any event, now coming up for a breath of air, may I expand a little on the model for you ... and for Naydene, to whom I shall send a copy of this letter, for her records.

For each of four hundred odd cells, which are coupled to one another to simulate the fairly complex topography of the Methow, Chewack, and Twisp river valleys, a mass-conservation equation is solved at every time step:

$$dC/dt = -v\ dC/dx + K(d^2C/dx^2 + d^2C/dy^2) + Q - k\ C \qquad [1]$$

v = the wind velocity, which is oriented in the up- and down-valley directions (x),

K = a diffusivity,

Q = a local source, if any, and

k = a 'ventilation coefficient', which accounts for losses out of the cells and into the air above the valley-bottom boundary layer.

All these four coefficients are time dependent, but are specified externally rather than solved independently.

At each time step, [1] is solved by an algorithm which conserves all the local fluxes, into and out of each cell. Additionally, the tracer is conserved for fluxes into and out of the network of cells as a whole, but with a caution upon which I must amplify somewhat.

Convergence of TRACER concentrations at individual cells is permitted, both through the eddy terms by down-gradient diffusion, and through the velocity term by advection from the upwind cells, but [1] has no term in it to account for convergence of MASS, because v(t) is constrained to be everywhere uniform, at any given time.

This constraint is unphysical for horizontal flows in closed valleys, where ... as in the present case ... the valley cross sections vary, and the sum of cross sections at the upwind valley heads do not equal that at the valley foot. Strictly to conserve mass, one must postulate compensating 'leakages' across the valleys' transverse and upward boundaries. That something like these leakages actually occurs is evident from the observation that wind velocities throughout the lengths of the complex valleys remain more constant than their cross sections. Indeed, they remain nearly constant throughout the whole valley floor.

This difficulty is intrinsic with two-dimensional models, such as this one, having reflective boundaries. Three natural ways may be suggested to treat the difficulty:

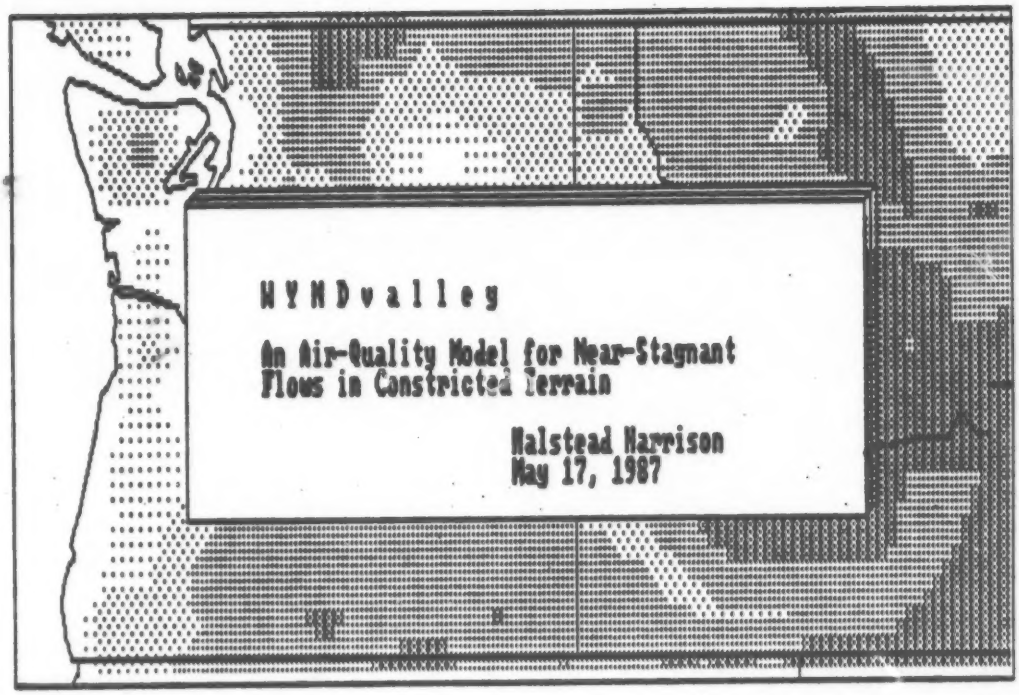
1. The lateral and vertical leakage rates might be adjusted to conserve mass for the network as a whole.

2. The cell heights might be adjusted in such a way as to conserve mass for the network as a whole. This would result in the upwind cells deflating ultimately to the surface during the downvalley wind surge, and conversely. The ventilation term might be parameterized in terms of the local cell heights.

3. Combinations of the 1. and 2..

Various sensible ways may be thought of, but none is uniquely suitable and some arbitrariness is inevitable. Further, the data base in most cases ... including the present one ... is usually too meager to arbitrate among plausible assumptions.

After some discussions with Mr. Rob Wilson, of EPA's region X, I chose not to attempt strict mass balance of the network as a whole, but to proceed to a direct solution of [1] with reflective lateral boundaries and constant cell heights. This approximation, which I emphasize is one in a continuum of alternative approximations, may if one wishes be thought of as resulting from time-dependent 'asymmetric diffusion', where in part of a cycle the down-valley 'diffusion' occurs with higher rate than the up-valley, and conversely in the other part of the cycle. For myself, I do not too much like such a description, as unphysical; however, in the finite difference formulation of [1], the two transports do appear equivalently as linear weights multiplying the local and the two adjacent up- and down-valley concentrations, and the partition of the whole transport into diffusion and advection can be relabeled as a partition into symmetrical and unsymmetrical components of a generalized linear transfer matrix. As you hinted in your letter, it may be simply a matter of semantics, though I hope you will not judge me flip in any way in this discussion of it.


HYNDvalley
An Air-Quality Model for Near-Stagnant Flows in Constricted Terrain
Halstead Harrison
May 17, 1987